Understanding and Predictability of Integrated Mountain Hydroclimate

DRAFT WORKSHOP REPORT

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Executive Summary

Mountainous systems cover approximately 23% of Earth's land and are distributed across all continents. They can capture and store atmospheric moisture that is then cycled through the terrestrial surface and subsurface system, released to downstream communities, and cycled back to the atmosphere. Characterized by steep gradients, geological, ecological, and biogeochemical diversity, mountain hydroclimate is influenced by topographic forcing and elevated warming and is susceptible to large subseasonal to multidecadal variability and rapid changes. Global warming impacts, such as multidecadal declines in mountain snowpack, longer growing seasons, and increased frequency and severity of extreme events like droughts and wildfires, have cascading effects on terrestrial hydrological and biogeochemical cycles. However, such effects and their feedbacks on climate systems and surface-subsurface compartments are unknown. Another critical knowledge gap, given human reliance on mountain systems for stable water supply and quality, is understanding the implications of changing hydroclimate and extreme events on hydro-biogeochemical cycles across atmosphere, terrestrial, and human systems in mountain regions and beyond. The increasing vulnerability of mountain systems to climate change and human perturbations motivates the need to improve understanding of integrated mountain hydroclimate systems and their feedbacks and impacts on humans across scales. However, with large heterogeneity and strong gradients, coupled natural-human processes in mountain regions present significant challenges for observations, modeling, predictions, and projections.

In this report, "integrated mountain hydroclimate" is defined as the collection of system components and complex processes in mountainous regions—spanning the deep subsurface, surface, and atmosphere—that interact at multiple spatiotemporal scales in response to natural and human influences.

Motivated by gaps in mountain hydroclimate understanding, observing, and modeling and the need for credible projections of future changes, the U.S. Department of Energy's (DOE) Biological and Environmental Research (BER) program organized a virtual workshop on "Understanding and Predictability of Integrated Mountain Hydroclimate." Sponsored by BER's Earth and Environmental Systems Sciences Division (EESSD), the workshop aimed to inform and catalyze EESSD's growing interests in enhancing predictive understanding of integrated mountain hydroclimate. Organizers structured the workshop to identify (1) knowledge gaps, (2) observational and modeling challenges, (3) research opportunities in the short (i.e., 1 to 3 years) to long term (i.e., 10 years and beyond), and (4) strategies for fostering collaboration and coordination. To address the outstanding challenges of integrated mountain hydroclimate, the workshop included two sessions organized by disciplinary, cross-disciplinary, and crosscutting science topics. The disciplinary and cross-disciplinary topics focused on essential elements of the integrated mountain hydroclimate: atmosphere, terrestrial, and human systems and their interactions. Breakout sessions on the disciplinary and cross-disciplinary topics facilitated identification of crosscutting topics and central emerging themes. Session 1 focused on connecting existing DOE investments to accelerate progress related to scientific challenges in understanding mountain hydroclimate. In Session 2, participants further explored key takeaways from Session 1 through the lens of multiagency collaborations and coordination.

The figure below summarizes the workshop goals and structure. For Session 1, key findings that emerged from the disciplinary and cross-disciplinary topics are summarized by the thematic outcomes, and the discussions on the crosscutting topics are summarized by the integrated activities. This report also describes the multiagency activities, coordination, and collaborations discussed in Session 2.

Fig. ES.1 Workshop Goals and Structure.

Science Gaps, Challenges, and Research Opportunities

The science gaps, challenges, and research opportunities identified at the workshop are synthesized by thematic topics and discussed below.

Mountain Extremes

Extreme events occurring in mountain regions include heavy orographic-driven precipitation, rain-on-snow events, rapid and early onset snowmelt, hot droughts driven by temperature and evaporation anomalies, snow and precipitation droughts caused by temperature and precipitation anomalies, and wildfires resulting from anomalies of temperature, humidity, soil moisture, fuel load, and fuel moisture. Extreme events present major threats to mountain ecosystems and play important roles in the global climate system and in broader energy, water, and food security. Threats and impacts to humans from extreme events in mountain regions include flooding, power outages, critically low water yields that affect hydroelectric power and agriculture, and nutrient loading. Considering these impacts, research on extremes in mountains and their future intensification is critical. While much research has focused on the drivers of extreme events, there are major gaps in (1) quantifying thresholds and tipping points before and after extreme events, (2) determining the scales at which extreme events interact to cause downstream impacts, (3) identifying feedbacks of extreme events on the regional and global hydrological cycle, (4) understanding changes of extreme mountain phenomena in the coming decades, (5) assessing the threat of growing water demand, and (6) examining mitigations of extreme event risk to agriculture, water supply, and water demand and quality. Workshop participants also highlighted compounding extreme events, such as snow droughts and wildfire, as critical research gaps because of their interdependence on each other and on mountain hydroclimate regimes, their vulnerability to changing snow conditions, and the direct human influence on wildfire risk associated with expansion of wildland-urban interfaces along mountain foothills. These knowledge gaps present the following research opportunities:

- Advance the understanding and modeling of snowpack spatial distributions and regimes that drive extreme events—including rain-on-snow flooding and compound extremes related to snow drought and wildfires—by developing long-term, spatially comprehensive, and frequent observations of snowpack.
- Improve quantification of the downstream impacts of extreme events and thresholds and tipping points by developing long-term datasets of mountain biomes to quantify ecosystem steady states before extreme events.
- Understand a range of system outcomes of extreme events by leveraging paleo- and synthetic data combined with *in situ* and remote sensing data.
- Gather critical extreme event–scale data using rapidly deployable observational campaigns.
- Improve the entire chain of models, encompassing weather, climate, hydrology, ecosystems, and risk, to understand feedbacks of extreme events on the hydrological cycle and develop novel and transformative mitigation strategies.
- Better understand extreme event thresholds and disentangle anthropogenic land-use factors from atmospheric and terrestrial influences by leveraging the co-benefits of nontraditional experimental campaigns such as controlled forest management.

Scaling of Mountain Processes and Data

Understanding the spatiotemporal scaling of processes and data is difficult in mountain regions at short and long time scales. The challenges arise from these regions' large topographic gradients, heterogeneous biomes, and varying land cover and use, which can amplify the spatiotemporal variability of hydroclimates and their response to anthropogenic activities. Undersampling the extreme spatiotemporal variability of mountain regions limits the ability to scale mountain processes, such as orographic precipitation, snowpack distribution, streamflow generation, and biogeochemical fluxes, and limits use of this data as model inputs and benchmarking datasets. Additional observational and modeling challenges arise from the spatial connectivity within mountain regions through surface and subsurface hydrology and between mountains and their upstream and downstream regions through atmospheric processes and connected human systems. Important gaps and challenges include (1) a wealth of data exists but has yet to be fully curated, quality controlled, and utilized; (2) observational networks are not keeping pace with increasing modeling needs; (3) gridded products have limited to no validation in mountain regions; (4) undersampling across elevation gradients with limited temporal coverage leads to simplified interpolation products with limited value for climate variability and climate change analysis time scales; and (5) spatiotemporal scale mismatches among measurements, modeling, and decision-making prevent realization of the full potential of EESSD's model-experiment (ModEx) approach (ess.science.energy.gov/modex/), especially at climate variability/change time scales. These challenges may be addressed through the following opportunities:

- Determine and close short- and long-term spatiotemporal observational gaps and optimize experimental sampling design using systematic approaches.
- Improve sampling of spatiotemporal variability to understand scaling of mountain processes using flexible, nimble, and networked mobile data collection platforms (e.g., artificial intelligence–guided, 5G, and autonomous frameworks).
- Bridge scales by using, for example, space-for-time approaches (i.e., substituting temporal sampling with spatial sampling across environmental and mountain gradients), paired catchment studies, and new upscaling approaches between point measurements and remote sensing to leverage the wealth of temporal data at point scales.
- Improve gridded products by integrating multisource, multiscale datasets from vast observational networks for value-added products and data harmonization using artificial intelligence (AI) and machine learning (ML).
- Better leverage underutilized data by more comprehensively and systematically integrating and analyzing data from past field campaigns and developing new ways to incorporate these data into state-of-the-art models as a pre-ModEx activity before designing and developing new operational and observational networks.
- Facilitate knowledge transfer and promote the use of observations for model development and evaluation through better coordination of long-term collaborative research stations and networks across different global mountain regions and develop research networks that involve scientists and stakeholders as partners at the onset.
- Generate new theoretical and conceptual scaling constructs of mountain regions by producing and combining multiple independent data streams, such as geophysics, hydrometrics, and tracers, into subsurface-through-atmosphere data collages.
- Enhance decision-making by collecting and analyzing data across systems and scales using citizen science, crowdsourced data, and integrated social science and community engagement.

Modeling and Prediction of Mountain Processes

Many processes important to mountain hydroclimate are missing or poorly represented in coupled modeling frameworks, limiting the ability to understand and predict bedrock-through-atmosphere processes in mountain systems, particularly in the face of change. To address mountain hydroclimate challenges, coupled modeling frameworks should include novel process-based coupling (such as deep bedrock fracture flow coupled with vegetation) and microbial biogeochemical cycling from deep bedrock weathering as a response to and a driver of atmospheric feedbacks (e.g., carbon dioxide release). Notably, even small-scale storms can significantly affect flooding, and hillslope-scale hydrological processes can create hot spots and hot moments of biogeochemical activity with large signatures that feed back to the atmosphere, highlighting the need to model multiscale processes in mountain regions. Major challenges in modeling and prediction include (1) determining the process representation and spatial resolution needed to credibly simulate mountain hydroclimate variability, change, and feedbacks in different regions; (2) advancing rudimentary observations, understanding, and modeling of system feedbacks, tipping points, and steady states in mountain systems; (3) developing benchmark observational datasets needed for model evaluation; and (4) improving the limited representations of human systems in modeling of integrated mountain hydroclimate. These challenges highlight the following opportunities for advancing modeling and prediction of mountain hydroclimate:

- Inform model development and experimental design by systematically evaluating the impact of model complexity, resolution, coupling, and ensemble size.
- Address cross-disciplinary scaling challenges by developing benchmarking datasets and novel metrics where science gaps exist, including (1) orographic precipitation, (2) concentration-discharge relationships, (3) evapotranspiration and atmospheric carbon fluxes, (4) wildfires, (5) human system components (e.g., related to infrastructure operations, wildland-urban interfaces, cloud seeding, or water management activities), and (6) spatiotemporally dense precipitation.
- Improve coupling of bedrock-to-atmosphere processes for models across a range of resolutions, including representation of process interactions at the subgrid scale.
- Overcome limited understanding of system feedbacks and tipping points in mountain systems through enhanced modeling of bedrock-through-atmosphere coupling.
- Represent human systems in models of mountain regions by developing a typology of human systems and their interactions with other mountain processes.
- Advance the design of novel numerical experiments to understand system feedbacks and tipping points in mountain hydroclimate changes through hierarchical modeling of atmospheric, terrestrial, and human systems and their interactions for mountain regions, including models of different complexities and configurations.
- Better represent human systems in models by developing new testbeds that leverage historical observational datasets and stakeholder community input.
- Develop benchmarking datasets and design modeling experiments and intercomparisons that integrate model transferability in the entire modeling process, from developing models to developing diagnostics and metrics for model evaluation.

Data-Model Integration in Mountain Regions

Although many past and ongoing studies include aspects of both modeling and observations, critical gaps in data-model integration exacerbated for mountain regions limit advances in mountain hydroclimate understanding and modeling. One challenge is the limited ability to use data in models because the data do not adhere to model spatiotemporal and quality assessment/quality control requirements (e.g., data from rugged terrain, limited spatiotemporal footprints, and absence of wireless networks to transfer data in real time). Another gap involves breaks in the ModEx cycle due to limited observational and numerical experimental designs that precede model development. In addition to the research opportunities discussed in the previous two sections, the following opportunities emphasize data-model integration to jointly advance data and modeling capabilities:

- Close spatiotemporal gaps and improve availability of mountain modeling datasets by expanding collaborations with research and nonresearch partners (e.g., local agencies and technology firms).
- Integrate measurements, multiscale models, and ML to inform observational needs and model development for improved understanding and modeling of mountain systems.
- Advance and expand model-data integration approaches for mountain processes by using, for example, instrument simulators in models to more directly compare what instruments observe and what models simulate. Also employ real-time data assimilation to integrate data with models and conduct observing-system simulation experiments to evaluate the value of a new observing system before its deployment.
- Better represent critical mountain processes, including hydrological, ecological, and human systems, in current Earth system models by developing AI emulators based on data and model simulations.
- Improve modeling of atmosphere-terrestrial-human interactions and feedbacks using hierarchical modeling capabilities that represent cross-scale interactions of atmospheric and terrestrial processes to enable ModEx-based explorations.
- Harmonize and integrate terrestrial and human data to the same spatiotemporal resolution to facilitate generalization of human-Earth interactions. For example, use AI/ML models to integrate field experiments and other data.

Uncertainty in Mountain Hydroclimate Research

Understanding and quantifying uncertainty in integrated mountain hydroclimate research remain outstanding challenges. Key unanswered science questions for mountain systems are: What are the scales and spatiotemporal distributions of model, data, and predictive uncertainty, and how is decision-making impacted by the uncertainty in these distributions that propagates through the chain of model outcomes for atmosphere, terrestrial, and human systems? Correspondingly, major science gaps include (1) quantifying and attributing uncertainty due to downscaling approaches, model resolution, and model representation; (2) understanding the roles of system feedbacks in uncertainty propagation; (3) evaluating the impact of inadequate or missing representation of human multisector dynamics on uncertainty; and (4) communicating uncertainty to stakeholders and decision-makers. Workshop participants identified several research opportunities to address uncertainty:

- Quantify and attribute model uncertainty by developing multimodel and large ensembles featuring different modeling approaches, simulations with and without model couplings, simulations at different modeling resolutions, and perturbations of initial conditions.
- Inform the changing risk landscape and tradeoffs to support decision-making by developing and using probabilistic modeling frameworks to address uncertainties.

- Understand the limit of predictability from subseasonal to multidecadal time scales through novel numerical experiments specifically designed to study predictability of integrated mountain hydroclimate and inform decision-making.
- Improve uncertainty quantification for extreme and compounding events, such as drought followed by heatwaves and wildfires, via Big Data mining and improve simulations coupled with measurements.
- Improve communication of the uncertainty, actionability, and decision relevance of modeling and prediction research through co-production of knowledge and data between scientists and stakeholders.

Integrated Activities

A synthesis of the thematic gaps, challenges, and opportunities summarized above highlights the needs and opportunities for further advancing research in integrated mountain hydroclimate through integrated activities on three crosscutting topics: extreme events and impacts, transferable knowledge, and actionable science.

- **Extreme Events and Impacts.** Extreme events and disturbances are typically defined relative to an historical baseline, but such definitions do not necessarily translate into the impacts of these events. There is broad agreement on the need to redefine extreme events in terms of their impacts, as determined by stakeholders, based on the unique characteristics of each mountain system. Using extreme-producing phenomena and their impacts as a central focus may accelerate progress in addressing gaps and challenges discussed in the "Mountain Extremes" section (see p. v).
- **Transferable Knowledge.** Mountain hydroclimates share many similarities, but they also differ due to variations in physical conditions, spatiotemporal scales of phenomena, and human systems management at upstream and downstream locations. Opportunities to enable knowledge transfer include (1) taking advantage of existing "network-of-network" groups to explore existing datasets across global observatories and identify process drivers, (2) designing model simulations to inform new measurements needed for different communities, and (3) performing model intercomparison studies across spatiotemporal scales and locations to inform drivers and responses to change.
- **Actionable Science.** Providing actionable science insights and predictions to support decision-making requires minimization of biases, since dynamical simulations are subject to uncertainties and errors. To advance actionable science, leveraging existing stakeholder engagements may provide important opportunities for defining the requirements and needs for simulations and observation data. Other approaches include co-producing knowledge and data, developing regional themes related to extreme events that disproportionately impact society, and quantifying the risk tolerance in decision-making.

Agency Activities, Coordination, and Collaborations

A need for long-term observational platforms and research to improve models motivates further intentional efforts to facilitate cross-divisional and interagency collaboration and coordination. Multiple EESSD-supported field campaigns and coordinated projects already feature cross-divisional collaboration on integrated mountain hydroclimate research. Some grassroots efforts also exist among scientists and agencies to foster networking and idea generation for future collaboration. Other modes of interaction to facilitate collaboration include: (1) "give-to-get" approaches in which a project supported by one agency provides data, modeling, and observational resources to a second project supported by another agency for an effort that fits within the other agency's missions but contributes to a shared program or goal; (2) "build it and they will come" scenarios in which field-based user facilities and community watersheds are developed with the goal of stimulating new funding by other agencies to support research in the same location and contribute to a shared vision; and (3) new shared funding opportunities whereby interagency teams develop and support research from the outset.

An interagency roundtable with program managers during the workshop highlighted that successful collaborations across federal, state, and local decision-making entities will require (1) Research-2-Operations (R2O) and Operations-2-Research (O2R) development cycles, (2) a shared understanding of the prediction problem, (3) approaches geared toward stakeholder co-production of research, (4) bottom-up and top-down collaboration business models, and (5) defining of priority regions. Because of the need for long-term observational platforms and modeling research for mountain systems, several opportunities were highlighted:

- Improve knowledge transfer and shared understanding by fostering more collaborations and comparisons across sites in mountain catchments instrumented around the globe.
- Connect with stakeholders by envisioning and executing storyline approaches focusing on how specific extreme events observed in the past may unfold in the future under climate change. Examples include "Miracle March," "Monsoon Rescue," and "Santa Slammers."
- Accelerate development of models and improve testbeds by expanding coordination across regions and programs that more optimally leverage observational datasets, stakeholders, and science communities.
- Leverage "community watersheds" that support and attract a community of researchers with common interests to facilitate increased collaborations through shared resources and goals.
- Enable knowledge transfer by guiding decision-making for new mitigation strategies to address the impacts of mountain hydroclimate extreme events.
- Facilitate grassroots and agency-driven mountain research collaboration by developing experimental watersheds to host long-term observational and modeling platforms.

1. Introduction

Mountainous systems cover approximately 23% of the global land surface and are distributed across all continents of the globe (Fattorini et al. 2020). Mountain systems can capture and store atmospheric moisture, which is then cycled through the subsurface and terrestrial system, released to downstream communities, and cycled back to the atmosphere. Over 40% of global mountains maintain a seasonal snowpack (Wrzesien et al. 2019). Because of the critical role of snowpack storage in providing water during dry seasons (Viviroli et al. 2007), mountain regions are “water towers” for major population centers. Mountain water resources support not only human activities, they are also vital to diverse ecosystems and biogeochemical cycles in the mountain environment.

1.1 Significance of Changing Mountain Hydroclimate

Mountainous systems are undergoing rapid climate change (Hock et al. 2019). Observations of amplified warming with elevation (Mountain Research Initiative EDW Working Group 2015), multidecadal declines in April snowpack (Mote et al. 2016) and increasing growing season lengths have cascading effects through terrestrial and aquatic ecosystems (Huss 2017), and on hydrological partitioning and water delivery (Rumsey et al. 2017). As extreme events become more severe due to warmer temperatures and associated increases in atmospheric moisture (Song et al. 2022), mountain hydroclimate may change nonlinearly and push historically assumed system behavior into conditions that have no historical analogs. Humans and ecosystems rely on mountain systems for stable water sources that are increasingly vulnerable to disturbances and extreme events induced by climate change. This vulnerability highlights the need to address challenges for predicting and understanding the role of integrated mountain hydroclimate systems and their feedbacks and impacts on humans across scales.

Changing mountain hydroclimate is projected to profoundly impact mountain water supply. Beginning with the water cycle, future mountain snowpacks are expected to decline and even disappear in some mountain ranges in climate-sensitive regions (Siirila-Woodburn et al. 2021). The complete loss of snow is the worst-case scenario. However, even a shift from rare or short-term occurrences of low-to-no snow to more persistent occurrences could significantly affect mountain resource management. Given projected declines and potential disappearance of mountain snowpacks and the importance of spring snowmelt in water management decisions, much research is needed to understand the drivers and processes underlying observed mountain hydroclimate changes. This research would enable scientists to assess current and future snow conditions in mountains across the globe and understand how these changes will impact water delivery downstream.

Atmospheric impacts on water partitioning have cascading effects on mountain watershed hydro-biogeochemistry. Since bedrock-through-canopy interactions can be a feedback of major greenhouse gas emissions to the atmosphere, a fundamental research gap exists regarding how these interactions and the biogeochemical cycles critical for regulating nutrient storage and release mechanisms will respond to changing water cycles. In one example in the Upper Colorado river basin, decadal declines in river exports of nitrate have been identified and associated with important vegetation, biogeochemical, microbial, and hydrological exchange patterns that are controlling this downward decadal trend (Newcomer et al. 2021). Understanding how watersheds retain and release essential elements in the face of changing climate in general, and changing snow conditions in particular, is important for understanding past and future changes in biogeochemical cycles not only in mountain areas but also in downstream regions through sediment, element, and nutrient (e.g., carbon and nitrogen) transport by rivers.

Future snowpack and other mountain-wide changes may have implications not only for water supply and hydro-biogeochemistry but also for local-to-regional circulation and teleconnections from mountain to lowland areas. For example, large perturbations of atmospheric flow by the Rockies can propagate downwind and influence the formation of clouds and precipitation in the U.S. Great Plains (Carbone and Tuttle 2008). Research is needed to examine how changes in hydrological processes in mountain regions may have long-range implications for atmospheric circulation and hydroclimate. Conversely, aerosol deposition on snowpack from long-range atmospheric transport could affect mountain snowpack, with subsequent local and remote influences through perturbations of the surface energy and water balance (Qian et al. 2009; Kassianov et al. 2017; Sarangi et al. 2020).

1.2 Workshop to Identify Research Needs and Opportunities

Motivated by the gaps in understanding and modeling mountain hydroclimate and the need for credible projections of future changes, the Earth and Environmental Systems Sciences Division (EESSD) within the U.S. Department of Energy (DOE) Biological and Environmental Research (BER) program sponsored a virtual workshop titled "Understanding and Predictability of Integrated Mountain Hydroclimate" to inform and catalyze EESSD's interests and approaches to addressing the scientific and societal challenge of enhancing predictive understanding of integrated mountain hydroclimate. In the context of the workshop, integrated mountain hydroclimate (IMHC) is defined as a collection of mountain subsystems, from the deep subsurface through vegetation to the atmosphere, that interact as a result of water and elemental movement and nature-societal interactions. Key natural processes controlling how energy, water, and biogeochemistry interact from bedrock through the atmosphere include water, energy, and elemental transport in the soil-plant-atmosphere continuum, vegetation and groundwater table dynamics, boundary layer turbulence, clouds and convection, and radiative transfer in the atmosphere and vegetative canopy. Key human-related processes that critically influence mountain systems include water infrastructure, forest management, land use, and agriculture. Important to the definition of IMHC are the dynamic interactions and feedbacks among various system components and influences that give rise to complex system behaviors, including compound extreme events and potential system thresholds and tipping points.

The workshop aimed to provide insight on priority challenges and regions and to identify future research needs and opportunities for increased collaborations among federal agencies. Participants addressed the following charge questions:

1. What are the key science gaps and questions and highest-priority research challenges in integrated mountain hydroclimate? Are there domain-specific science gaps that must be addressed to facilitate progress on integrated research challenges?
2. Are there highest-priority regions (within North America and globally) for focused research in mountain hydroclimate systems to address these science questions? Are there strategic regions to develop transferable knowledge and extensible approaches to apply at global scales?
3. What are some of the short- (1 to 3 year) and medium-term (3 to 6 year) integrated research opportunities to advance understanding and prediction of hydroclimate processes and interactions in mountainous regions?

4. What are the short- (1 to 3 year) and medium-term (3 to 6 year) opportunities within and across existing projects and BER Science Focus Areas to build more integrated frameworks that are extensible across multiple regions and employ leading-edge science approaches (e.g., integrated observatories; data-model integration; high-resolution, hierarchical, and hybrid modeling; multi-scale modeling; edge computing; and artificial intelligence and machine learning)?
5. What is the long-term (10 year) DOE vision for addressing integrated mountain hydroclimate challenges? What are the future opportunities and research needs, and how can the short- and medium-term opportunities and goals related to research challenges and existing DOE projects come together to meet this vision?

2. Workshop Structure

Integrated mountain hydroclimate (IMHC) research identified in this report will accelerate progress on four of the five grand challenges identified in the 2018 Earth and Environmental Systems Sciences Division Strategic Plan: integrated water cycle, biogeochemistry, drivers and responses in the Earth system, and data-model integration. IMHC research incorporates many disciplines and applications aligned with these grand challenges, including climate and atmospheric sciences, hydrology, biogeochemistry, ecology, and human multisector dynamics, all of which are connected by the integrated water cycle.

To address the outstanding challenges of IMHC, the workshop included two sessions organized by disciplinary, cross-disciplinary, and crosscutting science topics. The disciplinary and cross-disciplinary topics focused on essential elements of the integrated mountain hydroclimate: atmosphere, terrestrial, and human systems and their interactions. Breakout sessions on the disciplinary and cross-disciplinary topics facilitated identification of crosscutting topics and central emerging themes. Workshop co-chairs worked closely with the co-leads of the disciplinary and crosscutting topics to further identify and invite plenary speakers, panelists, and workshop participants. The workshop was conducted in a virtual format, with a total of 104 participants from U.S. and international universities, national laboratories, industry, and government agencies. To address the interdisciplinary challenges of mountain hydroclimate systems and to provide a broad range of perspectives, workshop participants represented diverse expertise in atmospheric, ecosystem, and watershed sciences; Earth system variability and change; and observational, experimental, and Earth and environmental systems modeling of both natural and human components.

2.1 Session 1: DOE FOCUS

This two-day session (November 15–16, 2021) focused on connecting existing DOE investments to accelerate progress on scientific challenges to understand the mountain hydroclimate system and associated processes. It provided a forum for scientists across a variety of academic, nonacademic, and federally funded research programs to present mountain hydroclimate-relevant projects and resources, including field campaigns and research projects, long-term field sites and investments, and modeling activities.

- Day 1 focused on disciplinary and cross-disciplinary science needs associated with three key topics: (1) atmospheric, (2) terrestrial, and (3) human system processes. Workshop participants discussed the current status, gaps, and opportunities in understanding, observing, and modeling of local processes, remote connections, and hydrological connectivity across multiple spatial and temporal scales from subseasonal to seasonal, and on to multidecadal variability and changes.
- Day 2 focused on three integrated, crosscutting topics and challenges: (1) human-terrestrial-atmosphere interactions, (2) IMHC variability and change, and (3) societal connections and implications. Workshop participants discussed the current status, gaps, and opportunities in understanding, observing, and modeling of human-terrestrial-atmosphere interactions in the context of diurnal and seasonal variability; extreme events; coupled water-carbon-nutrient cycles; IMHC variability and change, including contrasting different climate/hydrological regimes, responses to large-scale forcing; climate change impacts and processes in mountain systems; and challenges in connecting mountainous hydroclimate research to meet societal needs. Based on common themes that emerged from the disciplinary, cross-disciplinary, and crosscutting topical

discussions, workshop participants also discussed integrated activities focusing on three themes: (1) extreme events, (2) transferable knowledge, and (3) actionable science.

2.2 Session 2: Interagency Collaborations

This session took place on January 19, 2022. Participants from Session 1 were joined by program managers and project representatives from other federal agencies in addition to DOE. A set of key outcomes from Session 1 was presented by the workshop co-chairs at the opening of the session. This was followed by short presentations from multiple agencies and a roundtable discussion on ongoing activities across different agencies. Panel discussions were held on both the disciplinary (atmosphere, terrestrial, and human systems) and crosscutting (human-terrestrial-atmosphere interactions, IMHC variability and change, and societal connections and implications) topics. Lastly, a panel of program managers provided their perspectives on interagency collaborations on IMHC research and led an open discussion. Within the short presentations and discussions, key takeaways from Session 1 were further explored through the lens of multiagency collaborations and coordination.

Through plenary presentations, breakout groups, panel presentations, and roundtable discussions, workshop participants shared research goals and progress, identified gaps in understanding and modeling mountain hydroclimate, and discussed short-term (< 3 years), medium-term (3 to 6 years) and long-term (10 years) opportunities to address data, measurement, and modeling gaps. The detailed workshop agenda is provided in Appendix A, and the list of registered workshop participants is included in Appendix B.

This report summarizes the key outcomes of the workshop, with a focus on providing insights on priority challenges and future research needs for advancing understanding of IMHC. It also identifies opportunities to increase collaborations among existing EESSD programs, projects, and high-value synergies and to leverage EESSD investments and other federal agency efforts. This report is structured like workshop: disciplinary science (Ch. 3), cross-disciplinary science (Ch. 4), crosscutting science (Ch. 5), integrated activities (Ch. 6), agency activities and interagency coordination and collaborations (Ch. 7), workshop agenda (Appendix A), registered workshop participants (Appendix B), and references (Appendix C).

3. Disciplinary Science

3.1 Atmosphere

Atmospheric processes across various scales play major roles in shaping the integrated mountain hydrological cycle. Small-scale processes, such as aerosol-cloud-radiation interactions, intersect with medium-scale processes, such as orographic circulations, clouds, and precipitation, as well as with large-scale processes, such as atmospheric rivers and teleconnections (see Fig. 3.1). Ultimately, these complex multiscale interactions influence atmospheric elevation gradients and spatiotemporal variability in temperature and precipitation timing, amount, and phase that shape the speed at which water is stored and transported from the headwaters to downstream communities that rely on it. Due to the multiscale aspects of atmospheric processes that shape mountain environments, a variety of approaches are needed to better understand how mountain processes interact across scales and will be uniquely affected by climate change in different global mountain regions. These include the use of long-term observational networks and shorter-term intensive field campaigns, paleoclimate proxies, regional high-resolution modeling, and long-range climate model projections.

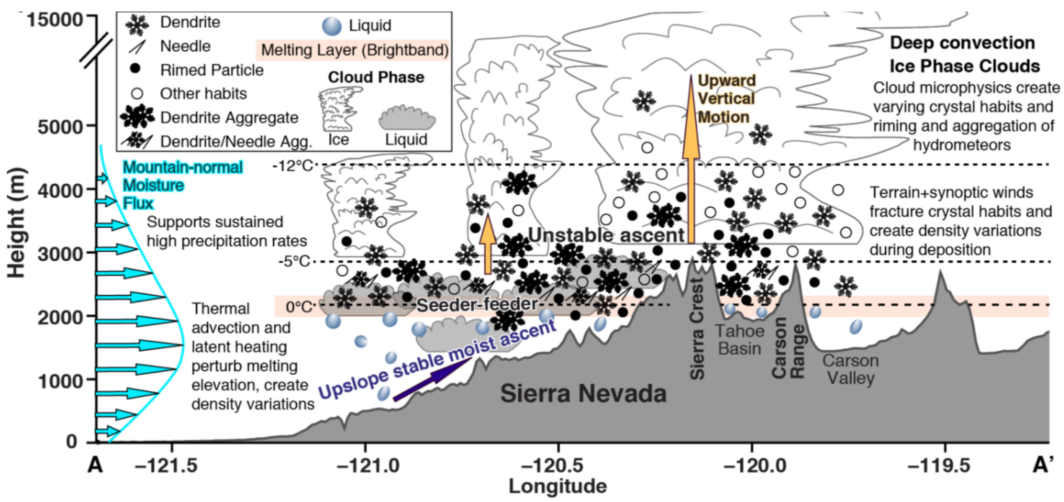

Fig. 3.1. Atmospheric Processes Relevant to Mountain Regions from Lowlands to Mountaintops. Mountain regions play a critical role in shaping the phase, distribution, magnitude, and intensity of precipitation. [Reprinted from Hatchett, B. J., et al. 2016. "Some Characteristics of Upside-Down Storms in the Northern Sierra Nevada, California-Nevada, USA," *Proceedings from the 2016 International Snow Science Workshop, Breckenridge, Colorado*. Copyright Montana State University Library 2022.]

3.1.1 Atmospheric Knowledge Gaps and Challenges

Understanding of atmospheric processes in mountain terrain has steadily improved over the last 50 years, leading to significant advances in prediction of mountain hydroclimate. However, many science gaps remain related to cloud processes, feedbacks, and scale interactions, all of which lead to challenges for modeling and predictive understanding. We describe the following four knowledge gaps and challenges: cloud processes in mountain terrain, atmosphere-surface interactions, cross-scale interactions within and downstream of mountains, and modeling limitations and tradeoffs in complex terrain.

Cloud Processes in Mountain Terrain

Mountain terrain influences atmospheric conditions that determine cloud radiative effects and precipitation phase, intensity, and spatiotemporal distribution. Critical cloud processes operating at smaller scales than can be resolved by modern weather and climate prediction models need to be parameterized, which introduces uncertainties and biases in cloud and precipitation properties. Mountain terrain forces multiscale circulations that form a complex array of clouds that are difficult to represent in models but important for the surface radiation balance, which can impact snowmelt and temperature as well as subsequent clouds and precipitation.

Hydrometeor phase partitioning affecting riming versus vapor growth that controls the type, location, and efficiency of precipitation remains poorly predicted. This influences where precipitation falls, with greater riming contributing to more windward slope precipitation and more vapor growth pushing precipitation toward the lee of mountains (Hobbs et al.1973). These processes depend on small-scale updrafts and similar scale topographic features that influence them, neither of which are sufficiently resolved in even high-resolution regional models (e.g., Kirshbaum 2020).

Much of the precipitation in many mountain regions is produced via convection that is initiated by topographically induced ascent (Kirshbaum et al. 2018). Many aircraft radar measurements show that convective circulations are even common in larger-scale stratiform precipitation with clear local enhancement of precipitation (e.g., Geerts et al. 2015), which is difficult to predict (Fuhrer and Schär, 2005). Deep convection also preferentially forms over and near mountain terrain due to orographic circulations, at times producing extreme precipitation events that are difficult to predict given the relatively small-scale nature of some storms. Combined with the channeling of runoff into canyons, mountain terrain is particularly susceptible to flash floods (Smith et al. 2018). Indeed, slow-moving storms that can be relatively small-scale can produce destructive flash floods in mountain terrain (Maddox et al. 1978).

Extreme precipitation and flooding over mountain terrain can also occur through sustained upslope flow, where collision-coalescence contributes significantly to precipitation amount (e.g., Gochis et al. 2013). However, these processes are difficult to predict due to their dependence on aerosol concentrations (Choudhury et al. 2019), which are modulated by poorly quantified precipitation scavenging of aerosols and complex orographic flow interactions (e.g., Muhlbauer and Lohmann 2008) as well as anthropogenic and wildfire emissions that are often absent in models. Mountainous terrain also often forms multilayer clouds due to deep tropospheric lift and cool, moist air trapped in mountain valleys or blocked flow. This can lead to seeder-feeder interactions that can double daily rainfall in mountain valleys and may be a major source of model bias because of the difficulty in resolving such cloud layers (e.g., Duan and Barros 2017). All these processes require further observational constraints and improved representation in weather and climate models.

Atmosphere-Surface Interactions

Clouds, precipitation, and surface state interact to affect mountain hydroclimate. The impacts of multiscale land-atmosphere coupling on mountain meteorology and surface conditions such as snowpack require inquiry across feedback pathways and scales. For example, rain-snow partitioning is largely assumed to be solely temperature dependent in most atmosphere and land-surface models, yet new research shows that surface humidity and winds can appreciably augment the presence of snowfall at above-freezing conditions (Jennings et al. 2018). Insufficient snowpack or surface moisture can warm and dry the boundary layer, feeding back to clouds and precipitation. There are also likely to be other feedback loops involving atmosphere and land surface processes, with implications for predicting mountain hydroclimate across scales (Siirila-Woodburn et al. 2021). Cloud and precipitation prediction errors consequently increase via their impacts on surface conditions and surrounding atmospheric circulation patterns that feed back to influence subsequent evolution of clouds and precipitation. Indeed, such feedbacks are not well characterized. These feedbacks may also impact much larger-scale circulations and remote regions via teleconnections (e.g., Letcher and Minder 2018), but such interactions remain poorly understood.

Cross-Scale and Downstream Interactions

Cross-scale processes in mountain terrain and their downstream atmospheric circulation responses are not well-represented in models. Higher-resolution models have led to substantially improved precipitation prediction over mountain terrain (e.g., Wang et al. 2018) such that they are now thought to outperform gridded observational retrievals that rely on statistical relationships to spatially interpolate in some data-sparse regions like mountains (e.g., Lundquist et al. 2019). However, this is not true everywhere, and a scarcity of robust observational data limits the ability to quantify model bias and truly assess the added value of resolution in many mountain regions such as the South American Andes (Condom et al. 2020; Thornton et al. 2022). Such models are also computationally expensive and are thus limited in domain size, simulation length, and ensemble possibilities.

Systematic analyses of coordinated regional climate modeling ensembles (e.g., CORDEX) have been invaluable in deciphering multiscale and intermodel differences in simulating mountain precipitation character (i.e., intensity, frequency, and duration). A key finding from these coordinated modeling efforts is that there is a clear, systematic improvement in modeled diurnal and seasonal precipitation when models are run at 3-km versus 12-km resolution across the European Alps (Ban et al. 2021). In addition, from an atmospheric circulation perspective, better resolving mountain terrain (e.g., Sierra Madres of Mexico) at higher resolution has been shown to mitigate a long-standing, systemic bias in the representation of the atmospheric general circulation (Baldwin et al. 2021), namely the double ITCZ bias, which has profound implications for downstream mountain hydroclimates (Dong et al. 2021).

Another long-standing modeling issue has been how to best represent boundary layer mixing in complex terrain with limited resolution. Many climate models lack the necessary vertical resolution, particularly in the boundary layer, to properly represent surface fluxes and mixing into the upper atmosphere that can, in turn, influence local microclimates and downstream atmospheric circulations. Further, boundary layer mixing parameterizations have largely been designed for flat, homogeneous terrain (Finnigan et al. 2020) and may generate too much stability in complex terrain, particularly over snow covered areas (Slater et al. 2001). This leads to erroneous surface temperature lapse rates at higher resolutions (Rhoades et al. 2018). Mountains must be emphasized more as important natural testbeds during model development, particularly to assess the added value of resolution, cross-scale interactions, and scale-aware physical representations.

Modeling Limitations and Tradeoffs in Complex Terrain

The necessary and sufficient model setup to assess mountain hydrological cycle processes, particularly when factoring in the regional importance of internal variability and scenario uncertainty is still unknown. The heterogeneity of mountain landscapes emphasizes the need for systematic evaluation of the necessary model setup in terms of resolution (both horizontal and vertical) and model complexity, both of which are required for climate models to sufficiently represent the mountain hydrological cycle. Model setup also needs to be juxtaposed in terms of its relative importance to both internal variability and scenario uncertainty in driving regional hydroclimates, and setups may differ from one mountain region to the next. To enable this advance, more internationally coordinated, high-resolution, multimodel ensembles assessed across a matrix of horizontal and vertical resolutions (structural uncertainty), ensemble members (internal variability), and socioeconomic development scenarios (scenario uncertainty) are needed (Gutowski et al. 2020; Schär et al. 2020). This effort would be better enabled, particularly at sub-3-km resolutions, if model code were adapted to new supercomputing architectures (e.g., graphics processing units) and support staff were available to handle and curate exascale data volumes to expedite scientists' analysis workflows.

Given limited computational resources, a balance needs to be achieved between model resolution, initial condition and perturbed parameter ensembles, and physics parameterization complexity, but the optimal balance for various weather and climate applications remains unclear, particularly in complex terrain. Furthermore, models are not equitably evaluated across global mountain ranges, hindering their utility in advancing hydrometeorological process understanding and climate impact assessments. At the same time, continued development of observational and modeling capabilities is required, which presents further challenges.

Differing scales, uncertainties, and complexities are required depending on the problem being tackled, but it is unclear which should receive priority and how resources would be best balanced across a range of problems and methods. Similarly, models are often built to predict mean states well, but more than ever they also need to predict extremes for which they may not be well suited (e.g., La Follette et al. 2021). Extreme events could act as potential opportunities to pinpoint process understanding and model representation deficiencies (e.g., orographic precipitation and freezing levels during atmospheric rivers) and model "blind spots" (e.g., downslope winds and wildfire-related impacts). Such events also could enhance usability of model hindcasts, forecasts, and projections for decision-relevant outcomes (e.g., Hatchett et al. 2020).

3.1.2 Atmospheric Research Opportunities

Several opportunities exist to make progress toward overcoming the atmospheric science gaps and challenges in mountain regions identified above. Namely, better leveraging existing data, data harmonization, expanding coordination among modeling activities, mining of large benchmark simulations, improved observational sampling and integration with models, and knowledge transfer.

Better Leveraging Existing Data

There is an opportunity to more fully utilize and synthesize the wealth of data that already exists from operational surface networks, research stations, and targeted field campaigns by connecting across these resources. Substantial data often remain unexplored, and some campaign objectives that depend on connecting several findings may not be fulfilled. The accumulation of underutilized data and unfulfilled potential from past field campaigns coupled with operational networks and state-of-the-art modeling present a major research opportunity. For example, DOE supported a recent field campaign in subtropical mountain terrain called CACTI. Collaboration with the RELAMPAGO campaign supported by the National Science Foundation (NSF) and additional contributions from Argentinean and Brazilian colleagues as well as NASA amplified the potential impact of research through shared datasets that multiple independent researchers could analyze and compare simultaneously. Similarly, the DOE-supported SAIL campaign's coordination and collaboration with the SPLASH campaign supported by the National Oceanic and Atmospheric Administration (NOAA) has resulted in collection of data covering multiple aspects of mountain processes. The SAIL and SPLASH collaboration represents an opportunity to use an unprecedented level of mountainous meteorological coverage to explore research questions related to scaling (upscaling and downscaling), novel inclusion of spatially and temporally complete datasets into process-based models (i.e., bedrock-through-canopy hydro-biogeochemical models), and exploration of transferability of mechanisms to other highly (and nonhighly) instrumented sites (see Box 3.1 for definitions). Tremendous time and effort are required to organize these large, multiagency campaigns, and they hold tremendous potential for interdisciplinary scientific breakthroughs due to their comprehensiveness relative to smaller campaigns.

Box 3.1 Definitions of Scaling, Transferability, and Storylines

Scaling: Methods to represent heterogeneity of states, mechanisms, processes, and parameters at different distinguishable scales

Transferability: Applicability and transfer of states, mechanisms, processes, parameters, and knowledge to new locations

Storylines: A physical climate storyline is physically self-consistent unfolding of past events, or of plausible future events or pathways. Storylines represent an alternative approach to representing uncertainty in physical aspects of climate change. They are inherently public-facing approaches to describing climate and meteorological phenomena.

Data Harmonization

A major hurdle for researchers to realize the full potential of so many underutilized datasets is a lack of standardized data formatting and quality control. In addition, datasets tend to be spread across a patchwork network of different data archives. Research efficiency and impact would likely be greatly amplified by expanding data harmonization and building data repositories. Many programs have large, organized repositories with readily accessible datasets in common, easy-to-use formats. A good example is the data center for the Atmospheric Radiation Measurement (ARM) user facility within the Earth and Environmental Systems Sciences Division (EESSD). However, not all atmospheric observation and modeling programs have put resources into creating such user-friendly repositories or adopting standard data and metadata formats. Such widely variable designs are an impediment to efficient research.

Efforts have increased to build repositories with graphical user interfaces that facilitate actionable science by stakeholders focused on specific topics such as Cal-Adapt. Projects such as GASSP have also recently started to harmonize extensive global datasets of specific properties (Reddington et al. 2017). While this trend is promising, these tasks are a small portion of what is possible. This could be because they require significant time and effort that are not sufficiently recognized, funded, or rewarded. Of first-order importance is agreeing on common variables (e.g., Thornton et al. 2021) and standardized naming and unit conventions for variables, which would allow for easier combinations of datasets from different observational and modeling programs over long periods. This is a tall task by itself given the number of datasets and variability among them, but it would be very impactful because of the statistical power it would bear, which circumvents a primary weakness of observations and their application to model evaluation and improvement: unrepresentative, limited sampling. To build the largest, most representative, and easiest-to-use datasets possible for model evaluation, improvement, and machine-learning (ML) applications, a common framework needs to be adopted by the wide range of measurement facilities across many different agencies.

Expanding Coordination Among Modeling Activities

On the modeling side, many projects have spun up and include both mountain hydroclimate and atmospheric process components. HyperFACETS, WACCEM, CASCADE, and CLASP are DOE-supported projects with some objectives that align with those of projects supported by other programs such as HiMAT, TEAMX, and ANDEX. Projects are often organized by region or storyline with multiscale foci ranging from regional mean climate to smaller-scale high-impact events. Some collaboration already occurs between project and model development teams, but more integration is possible, as are more interactions with stakeholders who can use the most relevant information to make societally relevant decisions based on predictions. These projects need to be maintained, but opportunities exist to expand coordination across regions and programs that more optimally leverage observational datasets and various stakeholders, as well as science communities, to develop model evaluation and improvement testbeds.

Mining of Large, Benchmark Simulations

Recent computational advances have led to projects implementing regionally focused historical and future climate runs (e.g., CORDEX) down to kilometer-scale grid spacing (e.g., Liu et al. 2017; Musselman et al. 2018; EXCLAIM). These advances significantly reduce precipitation and temperature biases in mountain terrain. Considerable resources are being spent to expand these further into global- and regionally refined kilometer-scale simulations using the DOE Energy Exascale Earth System Model (E3SM; Caldwell et al. 2021; Liu et al., in review). Although kilometer-scale simulations do not fully resolve mountain processes, such as orographic precipitation and its hydrologic impacts, they demonstrate obvious improvements compared to climate simulations typically run at grid spacing between 25 to 100 km. Seasonal-to-decadal kilometer-scale simulations are also feasible using regional models and global models with regionally refined meshes. However, kilometer-scale simulations are far from fully utilized, with ample opportunities to mine well-curated output from such simulations to target critical, uncertain processes. Large-eddy simulations can be used to probe more detailed processes over complex terrain. Further opportunities exist to better link model components from different communities (e.g., implementing snow models into mesoscale models or developing integrated atmosphere-through-bedrock modeling capabilities that capture the entire mountain hydrological cycle, including subsurface processes).

Improved Observational Sampling and Integration with Models

More than ever, opportunities exist to better integrate measurements, multiscale models, and ML for scientific advances, model development, and improved guidance of observational needs. While observations are a critical check on models, which often contain errors due to simplifications relative to the real world, observational sampling is limited and therefore representativeness errors are produced. Observations also measure a state rather than a process and often employ imperfect models to retrieve variables. Thus, models are also critical for informing and gap-filling observations. Advances in computing are opening opportunities to use high-resolution modeling with complex physics parameterizations, observational simulators, and ML to connect observable atmospheric-state properties to unobservable processes in novel ways. Such methods could also revolutionize data assimilation by overcoming linear operator limitations, observational networks, and targeted field campaigns through optimized designs for specific targets and improve prediction uncertainties via large, low-cost ensembles. Model ensembles also could be used to objectively determine which observations are most valuable and where they should be obtained. Models and observations have tended to focus on geographical regions such as the Rockies and the European Alps, which share some characteristics with other mountain ranges of the world (e.g., glacier retreat in a warming climate) but are also meteorologically unique. Even within relatively well-observed ranges, some microclimates remain poorly characterized. Remote, high ridgelines and peaks are poorly sampled by surface measurements (Thornton et al. 2022), while valleys are poorly observed by remote sensing. Yet, characteristics and processes within these undersampled regions each play critical roles in modulating atmospheric circulations that control precipitation intensity, duration, and location. It is possible that these sampling biases have skewed scientific understanding and model designs, which would potentially benefit from studying poorly observed ranges. However, there are also cases to be made for targeting mountain ranges that are expected to experience emerging climate shifts sooner or those that are most vulnerable or relevant to societal needs (e.g., water yields).

Research that embraces DOE's coupled Model-Experimentation (ModEx) approach (see Box 2.2) can be used to better inform observational strategies and guide these important decisions related to selecting locations and scales of priority regions. The strategy and success in this ModEx approach rely on early model application efforts to regions before any *new* observational campaigns are deployed by adequately synthesizing and testing pre-existing available and historical datasets as a pre-ModEx activity. There is also a need for model development in new regions to broaden the use of observational data that span multiple regions and components of the mountain hydrological cycle as a way of testing model transferability. This requires incentive structures that break down traditional scientific silos and the development of multidisciplinary teams to evaluate processes that span the atmosphere through bedrock.

Box 2.2 Definition of the ModEx Approach

ModEx: The ModEx approach integrates process research, which involves observations, experiments, and measurements performed in the field or laboratory, with modeling research, which simulates these same processes. This integrated loop ensures that models incorporate state-of-the-science knowledge about critical systems, and the resulting improved models can be used to guide field and laboratory research to inform future decisions

Knowledge Transfer

To achieve better predictive understanding of mountain systems and project future changes to them, a coordinated effort is needed to diagnose essential underlying mountain processes that will be impacted by climate change (e.g., snow albedo feedback and dynamical and thermodynamical controls on orographic precipitation). A hierarchy of models also needs to be leveraged to inform best practices in observational constraints and downscaling methods. However, insufficient communication and knowledge transfer between different communities with common goals have limited scientific progress. For example, while studies of weather events within the context of climate have become widespread, there has only been limited collaboration among top scientists and programs in these different communities. Efforts have been made to include more scientists from relatively data-sparse and study-limited regions into major modeling and observational initiatives, yet significant improvements are still needed. Many such efforts to date have focused primarily on North America and Europe. More inclusive and broader-scoped research studies spanning multiple data- and model-poor mountain regions around the globe (e.g., Africa and South America) are needed to understand fundamental mountain processes, how they are modeled, and how they might be affected under climate change and to ensure that they are extensible, transferable, and useful for planning and adaptation efforts. Knowledge and capability transfer between different countries requires better frameworks that more easily facilitate collaborations and communications among scientists and relevant stakeholders (e.g., Rhoades et al. 2022).

3.2 Terrestrial

Through accumulation and melting of snowpack, mountain regions are "water towers" for major population centers and agricultural regions. The role of mountains as water towers is reflected mostly on the regional scale, the scale at which mountains define the hydraulic gradient, with higher elevation regions contributing to lower elevation regions via lateral groundwater flow and its exchange with surface water. The associated processes on the catchment scale are largely driven by local topography, which defines the water and energy balance due to aspect, solar angle, and shading. The resulting water and energy gradients in mountain catchments can lead to highly localized spatial variability that can exceed the impact of regional climate dynamics (see Fig. 3.2). This multiscale spatial organization leads to a complex pattern of precipitation partitioning into evapotranspiration and drainage to groundwater and streams, which is often expressed in the natural vegetation pattern. As an example, different plant communities are observed on water-limited slopes versus energy-limited slopes. While the water-energy coupling leads to a complex spatial structure of generalizable traits (e.g., heterogeneous vegetation and water-energy storages and fluxes) in mountain catchments, generalizable processes such as water and material transport from the ridge to the valley may lead to similar, common characteristics within different components of mountain systems. An example of this is wetter valleys with thicker soils, which are again reflected in the vegetation present.

Disturbances such as wildfire, drought, insects, and changes in snow regime present additional challenges to predicting IMHC fluxes and storage regimes of water and element due to the incomplete understanding and representation of how terrestrial ecosystems evolve and feed back on other processes after disturbances. For wildfire, hydrological partitioning between runoff and infiltration will be coupled strongly to the post-fire evolution of soil, deep roots, and vegetation (Balocchi et al. 2020; Keeley and Fotheringham 1998; Lloret and Zedler 2009; Zedler et al. 1983), including the development of wildfire ash and burned soils as new layers in the soil profile (Cardenas and Kanarek 2014; Ebel and Martin 2017; Moody et al. 2016). Changes in hydrological water partitioning will control an array of subsequent watershed processes, including erosion and geomorphology, subsurface water flow paths and residence times, biogeochemical reactions, and fluxes of reactive and nonreactive elements to the river.

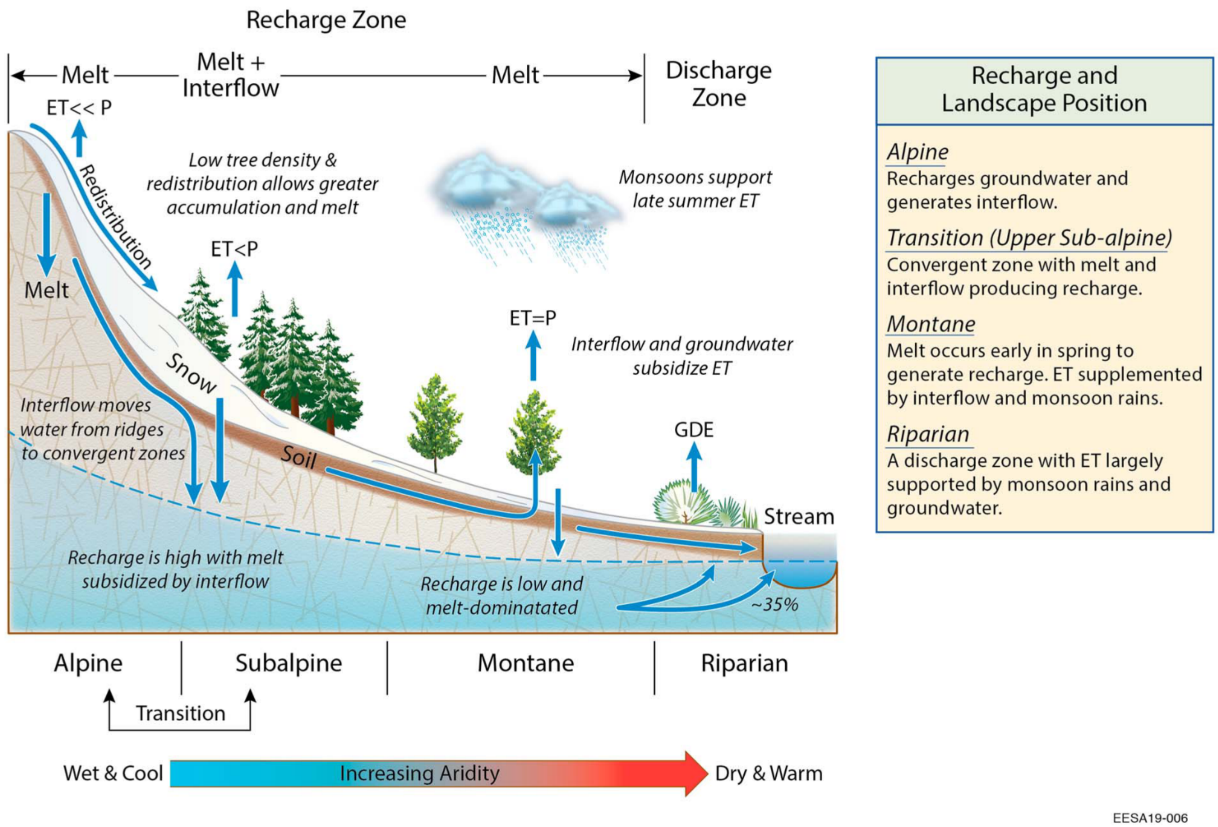

Fig. 3.2. Conceptual Model of Water Fluxes Across Large Mountain Gradients in Topography, Aridity, and Vegetation. Dominant mechanisms of the terrestrial water cycle in mountains are highlighted GDE=groundwater dependent ecosystem. [Reprinted under a Creative Commons license (CC-BY-NC-ND) from Carroll, R. W. H., et al. 2019. "The Importance of Interflow to Groundwater Recharge in a Snowmelt-Dominated Headwater Basin," *Geophysical Research Letters* **46**, 5899– 5908.]

3.2.1 Terrestrial Knowledge Gaps and Challenges

The large topographic relief and high elevation of mountain catchments amplify many challenges that are generally identified in terrestrial science. Therefore, the key research gaps identified below are not necessarily exclusive to mountain hydrology but are more pronounced for mountain systems due to the environmental conditions, complex bedrock terrain, and pronounced gradients from topography. The following challenges are highlighted: surface energy balance, surface and subsurface hydrology, soil-plant interactions and their relevance to ecohydrology and biogeochemistry, hot spots and hot moments, and terrestrial-climate feedbacks.

Surface Energy Balance

The complexity of mountain regions makes observing and modeling surface energy balance enormously challenging in these areas. For example, the intense spatial variability in aspect, slope, and canopy characteristics can lead to highly variable incoming solar radiation in mountain areas. This in turn has consequential impacts on the rest of the surface energy balance, including latent and sensible heat fluxes. Quantifying surface energy input is further exacerbated by the high temporal variability of snow albedo, which can be impacted not only by snow metamorphism and snowmelt but also by the deposition of atmospheric tracers, such as dust and black carbon (e.g., Skiles and Painter 2017), and ash from wildfires that exacerbates snowmelt (Pu et al. 2021). Hence, key challenges remain in robustly characterizing and quantifying the different components of the surface energy balance at multiple spatial and temporal scales over large mountain regions. As a result, significant research challenges persist in measuring, modeling, and benchmarking evapotranspiration, which is a function of the complex surface energy balance in mountains. For example, evapotranspiration fluxes highly depend on water availability in the terrestrial part of the water cycle, but they also are strongly influenced by the atmospheric interactions of air temperature, wind speed, and relative humidity.

Other challenges for obtaining surface energy balances over mountain regions are (1) identifying the degree of heterogeneity of surface states (e.g., snow cover density and snow water equivalent) and (2) understanding the key role of spatial connectivity among landscapes. To be more specific, processes such as snow drifting, secondary circulations, overland flow, and subsurface flows lead to highly interconnected hydrological systems that in turn have a large impact on surface energy partitioning. This makes observing the states and fluxes over these regions especially challenging. For example, the use of eddy covariance towers to estimate surface fluxes in the presence of secondary circulations (e.g., upslope or downslope flows) can be critically misleading. For mountain regions, identifying spatial and temporal snow cover distribution and persistence poses a specific challenge because snowmelt properties are difficult to track in real time at the level of spatial resolution needed to honor the inherent heterogeneity. *In situ* observations with innovative instrumentations range from cameras (e.g., Pohl et al. 2014) to temperature profiling systems (Dafflon et al. 2022) to remote- sensing approaches like the Airborne Laser Scanning applied on individual trees (Russell et al., 2021), and to entire catchments via the Airborne Snow Observatory (Painter et al. 2016). Despite these innovative approaches, problems with snow cover observations are further exacerbated when attempting ModEx approaches with local and Earth system modeling due to the need to resolve these fine spatial scales and interconnectivities more explicitly to enable appropriate process representation. There is general agreement that the modeling of surface fluxes over mountain regions is deficient due to the over-reliance on theories and parameterizations solely based on flat terrain.

Surface and Subsurface Hydrology

Subsurface water storage and its connectivity to streams play a crucial role in the partitioning of precipitation into groundwater recharge, stream discharge, and evapotranspiration. Subsurface processes are generally challenging to observe, but in mountain environments, access to study sites, relatively shallow soil depths, and high rock content with unknown fracture density distributions further pose practical issues for data gathering and model development. Thus, there is a pronounced lack of process understanding of mountain subsurface hydrology. In most mountain systems, there are significant unknowns related to the first principles of how much water is stored in mountain catchments (e.g., groundwater depth variation in space), how variable this storage is in space and time, and the drivers of storage changes (e.g., snow drought versus increases in evapotranspiration).

Wildfires also represent a critical perturbation to mountain regions through their impacts on surface and subsurface hydrological partitioning (Williams et al. 2022; Maina and Siirila-Woodburn 2019; Havel et al. 2018). Although wildfires are fundamental to the disturbance regime in many terrestrial ecosystems (McLauchlan et al. 2020), the record-breaking severity, duration, and frequency of recent "megafires" represent a regime shift that may lead to different hydro-biogeochemical responses across the surface-subsurface continuum (Stavros et al. 2014). Hydrological partitioning can include many nonlinear responses such as (1) increased runoff and decreased canopy interception, (2) increased base flow through decreased evapotranspiration, and (3) in some cases decreased runoff and increased infiltration through new macropore formation. These alterations can lead to cascading effects down mountain valleys. These unknowns lead to an inability to close even basic water budgets at subwatershed to basin scales under current and future hydroclimatic conditions and in response to disturbances.

Infiltration patterns and subsurface flow paths are highly heterogeneous and dynamic in mountain systems due to spatially complex snow patterns, large topographic gradients, fractured bedrock geology and vegetation distribution. As a feedback mechanism, subsurface hydrological flow paths can also impact spatial patterns in snow redistribution, sublimation, snowmelt rate and timing, and responses to variable hydroclimatology through controls on vegetation distribution that affect shading (Maina et al. 2020a; see also Ch. 4). These uncertainties in the understanding of stream water generation and groundwater recharge hinder a mechanistic implementation of the subsurface hydrology in regional- to large-scale land-atmosphere models.

An important research challenge is the representation of lateral hydrological processes (i.e., connectivity) in Earth system models (ESMs). For example, research has shown that lateral groundwater flow impacts evapotranspiration rates on continental scales (Maxwell and Condon 2016). Due to large topographic and hydraulic gradients, this effect will be very pronounced in mountain regions. However, challenges exist with the characterization of subsurface geological structure and the parameterization necessary to describe subsurface flow volume and its variability in time.

Another challenge is the scale-appropriate parameter representation of bedrock fracture flow paths and densities in both local reactive transport models and global ESMs. Currently, subsurface models represent bedrock fractures with effective van Genuchten parameters that do not reflect or accurately represent the physical fracture subsurface flow process. Recent DOE-funded work in the East River Community Watershed using large airborne electromagnetic measurements allowed derivation of shallow bedrock electrical resistivities across large areas of the watershed (Uhlemann et al. 2022). Such novel information can then be included in subsurface characterization of spatially distributed hydrological and biogeochemical models at an unprecedented level of detail required for process-based predictions.

For ESMs, approaches like the representative hillslope concept allow some degree of accounting for subgrid heterogeneity (Swenson et al. 2019), but relating observations on the plot or hillslope scale to simulations on catchment to basin scales remains a grand challenge (Fan et al. 2019). Unresolved scalability challenges include appropriate hydrological parameter representation on model grids of various coarseness and upscaling and downscaling approaches to refining and gapfilling input grid-based datasets (e.g., snow water equivalent, precipitation, and van Genuchten parameters). While novel high-resolution datasets provide the necessary inputs for next-generation, process-level hydrological prediction and understanding, obtaining these everywhere is not feasible. Thus, based on the desired outcome, a balance must be struck between simple “black box” predictions and true process-level understanding.

Soil-Plant-Root Interactions

Due to the spatial complexity in available energy and water distribution in mountain regions, the diversity of mountain plant communities, root distributions, and soil structures poses a challenge to understanding ecohydrological and biogeochemical processes. Dynamic feedbacks between soil and plants within the Critical Zone, spanning from bedrock groundwater to the plant canopy (Grant and Dietrich 2017), are difficult to observe and predict. This challenge occurs because most feedbacks take place at short temporal scales (Dubbert and Werner 2019) and small spatial scales in the subsurface root zone (York et al. 2016) that are not observable without complex *in situ* equipment. Moreover, roots access soil and bedrock depths that are chronically understudied (Dawson et al. 2020). Soil-plant-root interactions are a highly interdisciplinary challenge because of the interplay of water and nutrient cycles that occurs at these interfaces. A proper understanding of soil-plant-root feedback loops is crucial to enable model predictions of fluxes along the continuum from soils, plants, and roots through the atmosphere since these interactions are so sensitive to climate change (see Sections 4.1 and 5.1). Projections of ecohydrological interactions into a nonsteady future with hydro-meteorological drivers ranging from earlier snowmelt to longer drought periods or wildfires will require accurately representing how plants will respond to such extreme events. Wildfires can induce changes to nutrient and soil biogeochemical cycles, soil and rhizosphere microbiomes, vegetation structures, and feedback mechanisms across these compartments (Bouskill et al. 2022; Dove et al. 2021; Graham et al. 2016; Lloret and Zedler 2009). Therefore, important challenges to address include field observations and model implementation of (1) plant root depth, distribution, and potential for water uptake; (2) biogeochemical cycling; (3) hydraulic redistribution; and (4) root feedbacks on bedrock fracture distribution and element liberation.

Ecohydrological Interfaces and Biogeochemical Cycling

Ecohydrological interfaces, including river and riparian corridors, are unique components in mountain areas because their relevance and control on river chemistry highly depends on the scales at which their features function (Gomez-Velez 2014). The confluence of river channels, hillslopes, and floodplains are distinct features in mountain ecosystems, especially in headwaters where presses and pulses of water delivery from snowmelt, rainfall, and dry periods facilitate emergence of hot spots and hot moments of activity that have outsized influence at the small scales found in headwater systems (McClain et al. 2003; see Box 3.3). Confluences in these areas show signatures in their water, energy, microbiology, and biogeochemical cycles that can be noticeably different from surrounding watersheds and potentially reflect unique characteristics and mechanisms of the landscape (Newcomer et al. 2021; Matheus Carnevali et al. 2021). While these river and riparian regions occupy only a relatively small fraction of the headwater area, they can play a key role in ecosystem functioning in headwaters as revealed by their aggregated downstream signatures (Arora et al. 2020). Features of riparian corridors include meadows, hyporheic zones, and floodplains that are fundamentally smaller regions of the larger mountain area. These features can also impose a very large signature on stream chemistry and larger-scale biogeochemical cycles (Newcomer et al. 2018; Rogers et al. 2021).

Despite the importance of these interfaces in mountainous regions, many knowledge gaps and model-data integration approaches currently fail to represent the role of small-scale features, which leads to fundamental inaccuracies and misguidance in process attribution. While river corridor features and emergence of hot spots and hot moments are represented well in local, scale-appropriate models, their aggregated role (and the potential to predict this aggregated role) is fundamentally ignored in ESMs. This is partly because the observations of riparian corridors have mostly been dominated by local and catchment-level studies without a comprehensive evaluation of riparian corridors and their role on ecosystem functioning. The move of ESMs to include hillslopes processes (Fan et al. 2019) provides a promising path forward. However, this work is only now being coupled with modeled stream networks (Chaney et al. 2021). Outside of computationally intensive, physics-based models, there is a persistent need to bridge the scale gap between lab-to-field work and field-to-modeling work being done in hot spot and hot moment research and to re-imagine how modeling parameterization is conducted at each appropriate scale. For example, since hot spots and hot moments play such an outsized role in biogeochemical cycling, how do we adequately parameterize their mechanisms and level of influence without having to resort to millimeter-size mesh grids at all locations where they occur? More generally, there is a need to think about hillslopes, floodplains, and stream systems as interconnected functional systems instead of independent units, highlighting the need to develop research that considers novel functional zonation and characterization approaches (e.g., Wainwright et al. 2022; Chaney et al. 2018; Enguehard et al. 2022).

Box 3.3 Definitions of Hot Spots and Hot Moments

Hot-spot: Patches that show disproportionately high reaction rates (or other relevant mechanisms and parameters) relative to the surrounding matrix

Hot-moment: Short periods of time that exhibit disproportionately high reaction rates (or other relevant mechanisms and parameters) relative to longer intervening time periods.

Merging Data with Models Limited by Spatial and Temporal Resolution

While field observations have never been as extensive as those currently being performed, the coupling of gathered data with simulations remains challenging (Hubbard et al. 2020). The discrepancy between the temporal and spatial scales of observations and simulations limits the integration of field data into models (Clark et al. 2015). Subsurface data especially is commonly restricted to point-scale information, but the hydrological and biogeochemical response of catchments or basins is usually the scale of interest. Remote sensing of the land surface has been considered as a way to help scale up local observations; however, the extent to which remotely sensed surface and shallow soil (e.g., SMOS, SMAP) data allow for inferring subsurface structures has yet to be explored.

Although there is consensus that tracer data and widely available hydrometric data (e.g., discharge and soil moisture) will provide valuable insights into the flow and transport of water and its constituents (Sprenger et al. 2022), remote sensing cannot provide such information on transport processes. Therefore, intensive labor and extensive instrumentation are needed to gather hydrological and biogeochemical tracer data such as stable isotopes (e.g., of water isotopes for ^{2}H and ^{18}O or nitrate isotopes for ^{18}O and ^{15}N), ions, and dissolved organic carbon. Such information is orthogonal to the more common hydrometric data and adds opportunities to investigate velocities (e.g., how fast water and its constituents flow) in addition to celerities (e.g., response in hydrograph or soil water content; McDonnell and Beven 2014). Extensive tracer and solutes datasets are currently gathered from Colorado's East River by the DOE-funded Watershed Function Science Focus Area (SFA), and these have revealed new insights on groundwater recharge processes (Carroll et al. 2018), nitrogen export (Newcomer et al. 2021), and river gains and losses along stream reaches (Arora et al. 2020). Implementation of the tracer transport and the associated isotopic and/or biogeochemical processes into models will provide opportunities for multiobjective calibration approaches or benchmark tests of simulations. A recent example is the use of over 1,600 nitrogen concentration measurements from streams, groundwater, and vadose zone samples from the East River to calibrate a newly developed High-Altitude Nitrogen Suite of Models (HAN-SoMo; Maavara et al. 2021).

Terrestrial-Climate Feedbacks

The strong interconnectivity between the climate and mountain terrain is readily apparent in the high spatial complexity of the water, energy, and biogeochemical cycles that emerge due to elevation, aspect, parent material (and soil), and microclimate differences. Questions remain regarding how the role of these spatial pattern drivers will evolve under a changing climate. Wildfire critically impacts hydrological processes because of resulting vegetation loss, reduced evapotranspiration, increased hydrophobicity, and altered hydrological connectivity. A key challenge for models at various scales is simulating process-level interactions between atmosphere, vegetation, and the subsurface and how they feedback and respond to regional hydroclimatic conditions and wildfire events. Also unclear is how resilient the strong biodiversity across mountain regions is to sudden long-term shifts in the local microclimates.

In principle, ESMs offer the tools to answer the questions. However, the poor representation of spatial complexity over mountain regions in ESMs strongly limits their ability to inform terrestrial-climate feedbacks (Fan et al. 2019). This challenge arises not only from inadequate representation of the land surface and its interconnections but also from fairly *ad hoc* approaches to downscale coarse-grid meteorological variables to finer resolutions (e.g., radiation differences due to aspect) and upscale fine-scale parameters to more coarse resolutions. Ongoing DOE-, NASA-, and NOAA-funded terrestrial climate process teams (3Dland and CLASP) are seeking to address these weaknesses (Hao et al. 2021; Huang et al. 2022). Overall, combining recent process-oriented observations and long-term climatological studies is still a major challenge in understanding hydrological dynamics and process variability. This makes both quantifying and parameterizing these processes especially difficult. Consequently, increasing the availability and quality of remote-sensing data could potentially close the gaps by integrating ground-based and remote-sensing observations over existing and new mountain experimental watersheds. Links between the water and carbon cycles (e.g., greenhouse gas emissions) within the interplay of forests, soils, and water across mountain regions are especially not well understood.

3.2.2 Terrestrial Research Opportunities

Multidisciplinary Research to Characterize the Terrestrial Water Balance in Mountain Catchments

There are promising new multidisciplinary research opportunities to provide insights into subsurface hydrological processes. Using concurrent methods from geophysics, hydrometrics, and tracer hydrology to generate independent data streams of the terrestrial water cycle of mountain systems will result in new insights that would otherwise not be possible in a single-discipline approach. For example, geophysical measurements combined with tracer data allow for a novel scaling-up approach. This combined approach goes beyond the point-scale measurements of water storage and volume changes (e.g., Nielson et al. 2021; Angermann et al. 2017) to provide a novel method to study water transport and turnover rates in the unsaturated (Sprenger et al. 2016) and saturated zone (Jasechko 2019). As combined methodological techniques from different Earth science disciplines become more available, their application should be extended and intensified in the near term. In the longer term, these datasets provide a great opportunity to constrain or parameterize hydrological and biogeochemical models in multiobjective calibration approaches from plot (Sprenger et al. 2015) to basin scales (Stadnyk and Holmes 2020).

Mountain vegetative patterns may shift in response to an altered climate and disturbances and exhibit a feedback effect on the atmosphere as vegetation changes through cascading hydro-biogeochemical cycles (see Fig. 3.3). These shifts provide new opportunities to investigate ecohydrological linkages to determine how plants impact water and nutrient dynamics and vice versa. In summary, an ongoing challenge is to understand the changes in water partitioning into evapotranspiration, groundwater recharge, and catchment runoff depending on catchment characteristics and interannual variation of the in- and outflows.

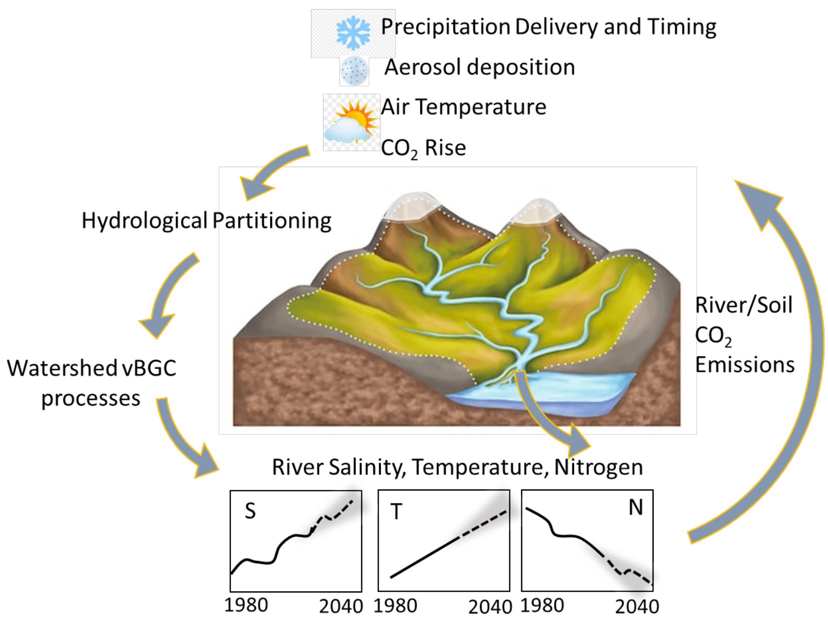

Fig. 3.3. Examples of Feedback Processes Across the Atmosphere-Through-Bedrock Interface in Mountain Regions. [Courtesy Lawrence Berkeley National Laboratory]

Model-Data Integration to Improve Predictability of the Mountain Terrestrial Water Balance in a Changing Climate

Efforts are underway to represent hillslope-scale subsurface hydrological processes in ESMs and to include catchment- to hillslope-scale observations for testing and benchmarking these models (Fan et al. 2019). Such developments in the near term can provide, for example, further opportunities to test the impact of lateral subsurface flow on the water cycle at large scales (Maxwell and Condon 2016). However, because consideration of subsurface hydrological processes in physically based mechanistic models is computationally expensive, ML approaches such as emulators provide an opportunity in the longer term to introduce simulations of complex subsurface flow patterns at large scales (Tran et al. 2021). In this context, integrating surface-subsurface exchange in hydrological models is an opportunity to include the impact of gaining and losing stream reaches along the large relief in mountain basins on the total water cycle (Dwivedi et al. 2018).

Novel experimental work that allows for controlled boundary conditions, such as the DOE-funded SMART soil testbed at Lawrence Berkeley National Laboratory or the NSF-funded Landscape Evolution Observatory (LEO) at Biosphere 2, provide research opportunities to investigate complex soil-plant interactions on small scales that need to be tested and transferred into field applications. Such controllable conditions enable testing innovative technology, such as the Tomographic Electrical Rhizosphere Imager (TERI) developed in the DOE-funded Ecosense effort or isotope tracer applications (Werner et al. 2021).

In the long term, improved connection between subsurface observations and remote sensing (e.g., Grace, Sentinel) will help bridge the scales and include catchment-scale process understanding and observational data in large-scale modeling. To observe environmental change (e.g., as vegetation shifts due to climate change, wildfires, or land-use changes), initiation of long-time-series observations need to be funded in the near term with a long-term perspective. Resulting large datasets will enable application of ML and artificial intelligence (AI) to improve the predictive power of environmental models. The overarching research question for the terrestrial water cycle in mountain catchments is how the water balance will change in a warming climate. More specifically, there is a need to understand the uncertainties related to precipitation (e.g., relative share of snow versus rain and drought frequency) and evapotranspiration (e.g., vegetation changes and plant physiological response to climate change).

Integrating Hydrological and Biogeochemical Process Understanding of Mountain Environments

To improve understanding of spatiotemporal coupling of biogeochemical and hydrological processes in soil, the capillary fringe, and the upper portion of the saturated zone, DOE supports research within the Watershed Function SFA, and the Floodplain HydroBiogeochemistry SFA. Building off these large-scale, field-based community watershed facilities, a long-term research opportunity is to study intensified connections between hydrological and biogeochemical processes, which will provide opportunities to relate water cycle changes with consequences for nutrient and contaminant transport. Model development that accounts for appropriate representations of water flows and input, transformation, and export of solutes will enable assessments of how changes in precipitation pattern and evapotranspiration dynamics in a warming climate affect water quality downstream of mountain headwater catchments. In summary, an important research question would be to understand how the water balance impacts the storage and release of carbon, nitrogen, and other constituents transported with water.

3.3 Human Systems

Predictability of the integrated human-Earth system requires detailed process understanding of the interactions among human and environmental systems across a wide range of scales. Indeed, human and Earth systems span a similar range of spatial and temporal scales, yet human systems science is still in its infancy in integrating with predictive ESMs (Reed et al. 2022). At the global scale, human activities aggregate to fundamentally influence Earth system processes through greenhouse gas emissions, aerosol emissions, and land-use and land-cover change (Riahi et al. 2017). At regional scales, human systems rely on and are vulnerable to changes within environmental systems that support critical infrastructure and the provision of resources such as energy, water, and food (Hoekstra et al. 2012).

Mountain systems provide an important context for examining human-Earth system interactions, both because of the critical services that mountains provide to human societies and because of the cross-scale interactions that take place between local and distal human and environmental processes in a mountain context. For instance, mountains are often conceptualized as the water towers of the planet, providing storage of cool-season precipitation in the form of snow and slow release of water supply during the warmer spring and summer months. Mountain processes thus drive downstream human systems through water availability (magnitude and timing) and water quality that are critical for infrastructure resilience, urban systems, and agriculture (Siirila-Woodburn et al.,2021). Mountains also provide important resources and services through biodiversity, minerals, forest products, tourism, and complex wind patterns that can be harnessed for wind energy.

Despite their significance to human societies, mountain regions remain sparsely inhabited compared to coastal zones and river confluences. Nonetheless, mountain climate, hydrology, and biogeochemical cycles are substantially impacted by humans. These impacts include the direct effects of human activities within mountains, such as operation of water infrastructure that alters streamflow, forest management practices that remove carbon and influence wildfire and hydrological regimes, and mining practices that affect water quality and biogeochemical processes (see Fig. 3.4). Mountains are also influenced indirectly by distal human activities including greenhouse gases that drive global climate change and aerosol emissions that deposit in mountains and influence snow hydrology. These bi-directional and cross-scale interactions among human and mountain systems create complex feedbacks with consequential implications for society.

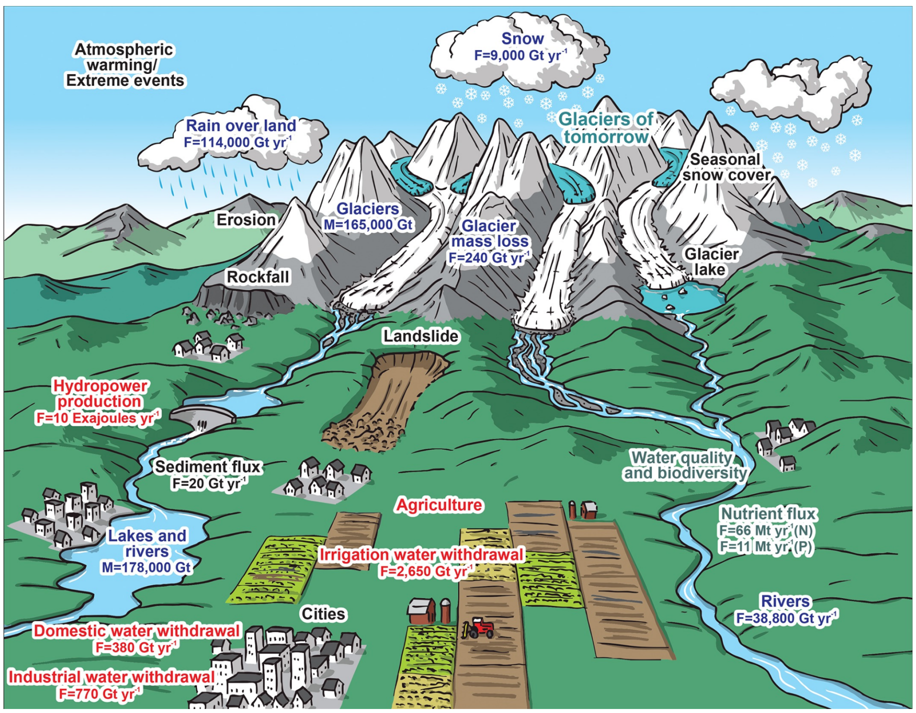

Fig. 3.4. Human-Mountain System Interactions. Human settlement is largely concentrated outside of mountain regions, yet societies rely on mountains for numerous critical resources and services. Mountain climate, hydrology, and biogeochemical processes in turn are influenced by human activities, both directly through resource management activities and indirectly through global and regional environmental change. [Reprinted under a Creative Commons license (CC-BY-NC-ND) from Huss, M., et al. 2017. “Toward Mountains without Permanent Snow and Ice,” *Earth’s Future* 5(5), 418-435.]

3.3.1 Human Systems in the Context of Mountain Hydroclimate Dynamics

Understanding human systems as part of mountain hydroclimate requires investigating a number of spatial and temporal scales. Because the diversity of human systems is not fully captured in models (and is most often modeled in isolation), there is an overall science gap in understanding interactions between human systems and mountain hydroclimate. While case studies from this workshop allow navigation of some data challenges, overall uncertainties remain large and there is still a need to address the transferability of local interactions to larger scales.

Local Mountain Human Systems

Locally, forest harvest is known to affect both mean annual flow as well as peak flows (Storck et al. 1998). The compound impact of forest roads and tree removal has been shown to affect mean annual flow while the impact on peak flow is influenced by the type of harvest (Lamarche and Lettenmaier 2001; Beshta et al. 2000; Wemple and Jones 2003). Forest harvest also affects sediment yields (Safeeq et al. 2020), which in turn influence a river's water quality to support biodiversity as well as man-made reservoir management. This further propagates to water-dependent human systems, including the energy sector (Hauer et al. 2018). From a human-systems perspective, while there are local land-management models, there is a disconnect with wood-sector models, which have been developed to evaluate climate change and greenhouse gas emissions (Werner et al. 2010) rather than local interactions and adaptation strategies.

Another type of local human system is human-made headwater reservoirs. These reservoirs in mountain areas affect local land cover, with associated changes in albedo, wind, water table, and terrestrial-atmosphere interactions (Hossain et al. 2012). Through river and human systems connections, headwater reservoirs in mountain areas provide several "river services." These services include flood control, water supply, navigation, recreation, hydropower, environmental conservation, and water quality for downstream uses. Because of the large topographical gradient, reservoirs in mountain areas provide the largest hydropower generation capacity by volume of water. Pumped storage hydropower systems rely on smaller lakes in contrast to conventional hydropower and are particularly efficient in mountain areas due to the high topographical gradient and low losses via evaporation. This water-energy technology could play an important role in U.S. decarbonization strategies given the value of energy storage for smoothing intermittent generation from renewables (Dimanchev et al. 2021). While hydropower provides valuable services to the power grid, in mountain regions it is connected via costly transmission lines due to complex terrain and landslide risks.

Connected Human Systems

Many downstream human systems, such as water and energy infrastructure and the sectors that rely on those resources, depend on mountain systems. For instance, downstream human systems are connected to mountain systems via rivers that supply water and are often supported by local mountain human systems such as reservoirs, which provide storage, regulate water flow, and generate hydroelectricity. Downstream human systems connected via the river system include the energy, agricultural, transportation, and industrial sectors. Some services are general across sectors, such as water supply security, flood control, and electricity, while other services, such as navigation, recreation, and environmental conservation, are more sector specific. Most of these services and connections are further described in Section 3.3 of this report, although a more general definition of human systems interactions has also been described in other scientific literature (Yoon et al. 2022).

Physically distal human systems also influence mountain systems in various ways through infrastructural connections, environmental connections, and governance of human systems embedded directly within mountains. For example, governance and policy in the wood sector of the U.S. economy regulates wood harvest in mountain areas; the power grid drives short-term releases of water from headwater reservoirs in coordination with the infrastructure protection and environmental conservation sectors; and the demands from the agricultural, industry, and urban water sectors drive weekly, seasonal, and even annual water storage and releases. Governance and policy factors further interact to influence the operations of headwater reservoirs across different services. For example, these factors can be combined to guide forest adaptation scenarios to manage wildfires, water resources, biomass, and economic recovery, all of which impact local- and distal-connected human systems (Povak et al. 2022). Notably, human systems in non-mountain areas also influence mountain hydroclimate and dynamics through policy and governance as well as emissions of dust and aerosols transported to mountains. These aspects are further addressed in Section 3.2 of this report.

Recent Advances in Human Systems Representation in Earth System Models

The coupling of human systems in ESMs allows inclusion of the intricate dynamics and feedbacks between Earth systems and human systems, which are essential for ESMs to address vulnerability to climate change (Leung et al. 2020). During the past few years, Earth-human system modeling efforts have led to improved capabilities in representing human systems and complex interactions, with a focus on both new couplings and endogenous processes.

E3SM (Leung et al. 2020; Golaz et al. 2022) has integrated dynamic land-use and land-cover change (LULCC; Di Vittorio et al. 2020), consistent with integrated climate and human system scenarios (O'Neill et al. 2016) and as provided by the Global Change Analysis Model (GCAM; Calvin and Bond-Lamberty 2018). E3SM also implemented a spatially distributed water management model that represents reservoir operations and water allocation/spatial distribution (MOSART-WM; Voisin et al. 2013a, 2017), relying on previous advances in representing river routing (MOSART; Li et al., 2013, 2015). Finally, E3SM also includes two-way coupling of irrigation and river-routing water management (Zhou et al. 2020) to further propagate the impact of dynamic LULCC onto the hydrological cycle. Together, these human systems enable a better representation of stream temperature, surface water–groundwater interactions, and overall distribution of water and energy fluxes. Building on the subgrid topographic representations in E3SMv2, coupling of GCAM with E3SM may be improved to better represent human-Earth interactions in mountain regions.

3.3.2 Human Systems Knowledge Gaps and Challenges

There are four fundamental gaps at the intersection of humans and mountain systems: (1) addressing and representing phenomena at scales that matter, (2) evaluating the impact of human activities, (3) assessing tradeoffs for decision-making, and (4) representing human systems in ESMs.

There is a gap in the representation of LULCC in mountain areas associated with different scientific foci and process representation across a range of models. Most often, LULCC in governance-scale human system models is associated with greenhouse gas emissions (Calvin et al. 2019) and is disconnected from process-scale human system models, such as those for forest management (Povak et al. 2022). E3SM, which operates at an intermediate scale, currently lacks information from both the governance scale and process resolution to represent mountain LULCC and interactions with hydroclimate processes. This gap is further exacerbated by a lack of data, since most forest practice models and studies are local and in response to local human systems and science questions.

Overall, the representation of water management is reasonable but particularly challenging in mountain areas because of their complex topography. For instance, small biases in inflow will drive unrealistic representations of reservoir operations. While generic operating rules can adapt to both inflow and changing reservoir characteristics to achieve overall reservoir operating objectives (Voisin et al. 2013b), the accuracy and structure of ESM simulations currently challenge the use of data-driven reservoir operations (Turner et al. 2020, 2021). In addition, human systems that are fully integrated into ESMs tend to be passive, with generic and static operating rules, but the nature of human systems is typically forward-looking and highly responsive, as represented by optimization schemes in river-routing reservoir models, where science questions are human-systems oriented (Turner et al. 2022).

As spatial resolution increases to represent mountain and adjacent nonmountain regions, the largest gaps include human system diversity. For instance, only human systems connected to mountain regions by river systems are represented in ESMs (i.e., river services; Voisin et al. 2017). There is a gap in the coincidence of datasets between the connected human systems, the river system connecting the human systems, and the observations of the mountain and downstream connected Earth systems, which motivate human systems operations and connections. Finally, human systems are highly diverse and the modeling fidelity of this diversity is already nonrepresentative in human systems, and even less so when integrated with ESMs.

Resulting Grand Challenges

The gaps in mountain and connected human systems lead to the following grand challenges in understanding and modeling integrated human-Earth systems.

Transferability and Scalability. Local case studies, observations, and models are not necessarily representative of all mountain-human systems and associated interactions, given the diversity in regional human-mountain climate drivers and contributions across scales (see “Transferability” in Box 3.1). No systems currently represent the range of scales in interactions between human systems and Earth system mechanisms, nor are observations and mechanistic parameters representative of systems at different scales (see “Scalability” in Box 3.1). Fundamental research questions include determining the phenomena and scales that matter for human systems and how mountain systems are changing at those scales and for those phenomena.

Extreme Events. Because of the high-resolution interactions between human and Earth systems in mountain regions, there is little understanding in the decomposition of extreme event drivers and how human systems specifically alleviate or worsen impacts. Current ESM representation of mountain-human systems supports the analysis of average processes and interactions, with perhaps better representations of droughts compared to floods. One fundamental research question involves understanding how human activities alter environmental processes and the probability of extremes, both locally and through teleconnections. Another involves determining which mitigation strategies are suitable for decreasing the impact on human systems and controlling the frequency, intensity, and extent of mountain hydroclimate extreme events.

Uncertainties. Predictability is what enables decision-makers to make complex choices about the future. Human systems rely on forward-looking knowledge (e.g., water management and agriculture), and there are large uncertainties in how foresight informs human systems across scales and sectors. Many fundamental research questions exist that currently preclude an accurate assessment of tradeoffs and scenarios. These questions involve (1) determining the tradeoffs among different scenarios and infrastructure choices, particularly in the context of limited water resources and cross-sectoral interactions; (2) identifying fundamental science needed to credibly evaluate those tradeoffs; and (3) assessing the scales and spatiotemporal distributions of uncertainty and determining how they propagate through different models.

3.3.3 Human Systems Research Opportunities

The challenges identified above as well as the overall infancy of human systems science and its integration into ESMs leads to numerous research opportunities. Long-term observational platforms and models are needed that include multisector dynamics that adequately capture the diversity of human systems. As described above, the challenges are to (1) understand and relay uncertainty and risk to end users; (2) inform decision-making under such uncertainty and evaluate tradeoffs among alternative options using basic science capabilities; (3) operationalize methods for scalability and transferability; and (4) fundamentally understand interactions among human and environmental systems through novel observations, theory, and increased interactivity among human and ESMs. The overall major opportunity is to develop a bridge between fundamental science and decision-making agencies responsible for management actions and to provide forecasts and information useful for operational decision-making. Examples of these opportunities are provided below.

DOE already supports existing initiatives with diverse experimental setups, such as storylines and hypothesis-based and exploratory ML approaches, to investigate the range of interactions among human systems and between human and Earth systems across scales. Examples include physical climate storylines (see Box 3.1; Shepherd et al. 2018), such as the "Miracle March" in 1991 when California experienced its worst drought since the Dust Bowl before record-breaking snowfall occurred in March, which tripled mountain snowpack. Near-term priorities would include addressing the transferability gap, perhaps through a typology approach in which phenomena with similar characteristics are grouped to develop theoretical insights into the phenomena, explain their drivers and consequences, and transfer insights from one context to similar contexts (Biagini et al. 2014). A typology of human systems in mountain systems, and their interactions with other human systems directly and via Earth system processes, might be worth considering. Developing this typology may require developing a framework for understanding complex interactions among systems and scales—including uncertainty propagation, feedbacks, interactions, co-evolutionary processes, and other aspects—for existing DOE projects and activities as well as those supported by other government agencies. The exploratory framework would need to be versatile given that human systems function differently than Earth systems.

To address the scalability and transferability challenge, a new knowledge and data co-production framework would be required, wherein practitioners and scientists work collaboratively to define critical science questions; identify key scales, phenomena, and metrics that matter for practical applications; and evaluate the usability and salience of new knowledge for decision-making (Bremer et al. 2017). This framework would require observations and modeling of the phenomena and scales that matter. Opportunities exist to (1) leverage observational datasets and stakeholder communities to develop model evaluation and improvement testbeds; (2) implement regional climate modeling focused on storyline development relevant to local communities; and (3) conduct use-inspired, basic discovery science, motivated by stakeholders (i.e., co-production) to link science to basic operational work.

As transferability and scalability are better understood, new frameworks and theories for understanding human-Earth interactions and regional drivers of mountain-human systems would still be needed for the scientific community to further address extreme events. Promising research opportunities exist to develop field observations across human and Earth systems and across relevant system scales and sectors. For example, observational campaigns that focus on forest management activities, such as controlled burns and thinning, are opportunities to leverage controlled experiments to disentangle anthropogenic factors from atmospheric, ecosystem, and hydrological processes and to guide decision-making. This activity would require partnering with local agencies, holding workshops, and utilizing local resources and staff to aid in monitoring activities. An element of workforce development and training for scientists would be required to ensure successful transfer of knowledge and communication in a co-production framework. The activities and capabilities of many agencies could be leveraged rather than reinventing the wheel for experiments and model development.

In the long term, there are opportunities to advance a framework for uncertainty propagation that include a probabilistic predictive understanding that can inform a changing risk landscape and tradeoffs among alternative pathways. New AI/ML approaches likely will be needed that extend complex datasets and help support coupling approaches while maintaining ESM scales and that also recognize that the value of AI/ML applied to science is different than when applied to human systems. Examples include developing and applying AI/ML approaches to predict downstream water yield or quality under no-analog climate scenarios or to inform user-guided scenarios and storyline wish lists. Integration of human processes into ESMs is another example that would require better leveraging of observational networks and review of process representation by both scientists and end users. These new modeling platforms would be key for examining which processes dominate critical outcomes of interest in different contexts. An important question to examine would be the warming level and context whereby climate change would overwhelm local effects of land-use change on hydrology.

4. Cross-Disciplinary Science

4.1 Atmosphere-Terrestrial

Processes that occur at the atmosphere-terrestrial interface are particularly complex in mountain environments due to the heterogeneous spatiotemporal patterns and feedbacks of environmental drivers and ecosystems. To fully capture the integrated mountain hydrological cycle, important feedback loops between terrestrial and atmospheric processes need to be understood. With climate change, atmospheric conditions in mountains are likely to become more variable, and their trends are likely to intensify. These might include punctuated precipitation patterns, altered temperature increases with elevation, decreased snowfall fractions, diminished and earlier snowmelt, and increased evaporative demand. All these alterations will interact and result in a modified response of terrestrial processes through vegetation shifts, altered runoff efficiency, subsurface recharge, and evapotranspiration changes, which, in turn, can result in nonlinear feedbacks to the atmosphere (e.g., wildfire). Better understanding of how these processes interact with one another and how they might respond to various climate change scenarios will be crucial in making more societally relevant predictions of the future.

4.1.1 Atmosphere-Terrestrial Knowledge Gaps and Challenges

Workshop participants identified five major atmosphere-terrestrial knowledge gaps: (1) vegetation dynamics and resolved evapotranspiration, (2) disturbance challenges and the ability to measure and model systems, (3) wind redistribution, (4) elevation gradients in precipitation and temperature, and (5) snow-dominated hydrology.

Vegetation Dynamics and Resolved Evapotranspiration

Vegetation plays a key role in atmosphere-terrestrial interactions, as it actively transforms terrestrial water to atmospheric water through evapotranspiration. Vegetation further affects the infiltration pattern of precipitation into the terrestrial subsurface. Both processes are spatiotemporally heterogeneous in mountain regions, which makes their assessment challenging. For example, evapotranspiration fluxes are highly dependent on water availability in the terrestrial part of the water cycle but are also strongly influenced by the atmospheric interactions of air temperature, wind speed, and relative humidity. The small-scale heterogeneity of available water storage (see Section 2.2) and hydro-meteorological drivers (see Section 2.1) make measurements of evapotranspiration (e.g., flux towers) in mountain catchments challenging. For similar reasons, simulating the actual evapotranspiration across mountain regions is difficult. Additionally, the discrepancy between the scale of observations and the scale of simulations further challenges an accurate representation of evapotranspiration fluxes in land-atmosphere modeling. However, an increase in evapotranspiration flux is identified as a major driver for observed mountain runoff reduction (Goulden and Bales 2014; Milly and Dunne 2020).

Disturbances Challenge the Ability to Measure and Model Systems

Another important aspect is linkages between vegetation patterns and the spatial variability of snow accumulation and melt, which includes canopy interception, long-wave radiation from stems, and impacts on wind distribution (Varhola et al. 2010). The large gradients in vegetation cover (altitudinal zonation) and precipitation volumes as well as the dynamic snow-to-rain transition result in a complex interplay between land cover and precipitation inputs into mountain systems. The consequences of these interactions for an individual plant's resilience to environmental stressors (e.g., drought, beetle infestations, and windfall) remain a grand challenge in mountain ecohydrology. One special aspect to consider is the interplay of atmospheric dynamics, vegetation, and the potential for an increase in forest wildfires. These dependencies are neither well understood nor widely implemented into Earth system models (ESMs). However, there are important impacts of wildfire on the hydrological processes due to post-wildfire vegetation loss, increased hydrophobicity, and altered hydrological connectivity. In addition, wildfires may impact soil erosion and dust emissions by reducing vegetation cover and soil moisture, with impacts on radiation, clouds, precipitation, and terrestrial biogeochemistry (Yu and Ginoux 2022).

Wind Redistribution

Although not well understood, wind is a crucial forcing on mountain hydrological processes and is thought to be a large driver for the spatiotemporal variability of available water in mountains. Wind patterns help determine the elevational gradients in snowfall, redistribution of snowpack, and magnitude of sublimation from the snowpack. While some general relationships between topography, wind, and snowdrift have been estimated, the impact of these processes on catchment-scale runoff dynamics and the snow volumes lost to sublimation remain elusive.

Elevation Gradients in Precipitation and Temperature

Precipitation and temperature gradients in mountains are considerable and undersampled from an observing-network standpoint. Stations are often limited to accessible areas. Thus, high elevations where precipitation, and especially snowfall, is highest and lapse-rates are maximized are not well sampled. As a result, different interpolation procedures have been developed through the years to provide a spatiotemporally complete estimate of these data gaps in mountains. Interpolation assumptions have resulted in a diverse set of gridded hydro-meteorological products that show considerable differences in even climatological statistical quantities, such as annual average precipitation and mean daily air temperature. Discrepancies in these gridded estimates have direct implications for estimating the magnitude and flux of terrestrial processes, such as surface runoff and subsurface recharge (Schreiner-McGraw and Ajami 2020), and for rain-snow partitioning, which shapes seasonal snow dynamics. Consequently, land-atmosphere models, which account for many of the physical interactions across the atmosphere-terrestrial interface, are now posited to outpace the skill of the observational networks (Lundquist et al. 2019). Additionally, the interpolation procedures built on empirical, geospatial, and/or climactic relationships now might not hold in a rapidly changing climate.

Snow-Dominated Hydrology

Snowpack is an emergent property of the mountain water cycle and a key driver of seasonal runoff. The emergent nature of snowpack, through its dependency on a myriad of atmospheric (e.g., precipitation, temperature, humidity, and winds) and terrestrial (e.g., vegetation cover and geomorphology) processes, make it particularly difficult to estimate and predict at landscape-resolving scales and especially in a changing climate. Although there is some disagreement in how mountain precipitation patterns will be altered by climate change, there is more certainty that temperatures will continue to increase, and, as a result, the fraction of precipitation that falls as snow and accumulates as snowpack will necessarily diminish. Therefore, important mountain-specific differences remain to be understood, particularly how the time horizons of persistent and widespread snow loss will differ across mountains. Critical mountain-specific changes might arise in the coming decades as precipitation increases, yet the freezing level in mountains can continue to reside at or near freezing at higher elevations. Changes in freezing levels may result in important regional differences in snowpack accumulation and supply at mid-century versus end-century. Regardless of the regional context of snowpack change, a reduced snowpack in the mountain environments will have several trickle-down impacts on water budgets and ecosystems. Diminishing snowpacks will have consequences not only on the headwater-to-valley hydrology but also on nutrient cycling, another poorly constrained process that is not yet widely represented in ESMs.

4.1.2 Atmosphere-Terrestrial Research Opportunities

Space-For-Time and Paired Catchment Approaches

There is great potential in intersite comparisons in which space-for-time approaches enable inferring hydrological response to altered atmospheric drivers. For example, extending observed gradients by combining mid-altitude to high-altitude and maritime to continental catchments can represent different snow dynamics and shed light on hydrological responses to a rapidly changing climate (and potential tipping points), particularly in rain-to-snow transition zones. Further, there is new intrigue in the concept of interseasonal repeatability of environmental patterns in mountains that might further support space-for-time analysis across global mountain regions. As several mountain catchments are already instrumented around the globe, a concerted effort to foster more collaborations across sites would be feasible in the short term. These international collaborations would provide new scientific insights and ensure that these insights could be vetted across different mountain regions (e.g., Early Career Network of Networks). In the long run, coordinated efforts with optimized instrumentation and sampling design would increase comparability across different mountain areas. Rapidly deployable observational campaigns (e.g., after disturbances such as wildfire) will be instrumental in providing “out of sample” estimates of mountain environmental conditions and enable revisiting priority environmental variables that need to be continually monitored (or their detail enhanced) in rapidly changing mountain environments (Newcomer et al. 2021b).

Hierarchical Modeling of Atmosphere-Terrestrial Interactions Across Scales

To improve the representation of the cross-scale interactions of atmospheric and terrestrial processes, hierarchical modeling capabilities represent a readily available approach to allow for simulations and predictions that cross environmental components. A hierarchical approach also enables systematic evaluation of the relative contribution of each process in shaping the integrated mountain hydrological cycle and, in turn, how each process individually (and collectively) shapes decision-relevant outcomes. Such modeling approaches have been available, but their focus has not necessarily been on mountain environments, nor have they incorporated an atmosphere-through-bedrock mindset.

In the short term, hierarchical experiments could be done with individual model components to test fidelity with and without coupling. In this effort, new insights from Atmospheric Radiation Measurement (ARM) sites and campaigns, such as SAIL, could serve in the near-term for model testing and improvements in atmosphere-terrestrial feedbacks. In the long-term, all model components would then need to be fully coupled and vetted. A fully coupled atmosphere-through-bedrock modeling capability would enable the interrogation of best-available understanding of mountain processes and their interactions and identify systemic biases that need to be addressed. Examples of such a research direction are DOE-funded efforts to couple the Community Land Model version 4.5 (CLM4.5) and a multiphysics reactive transport model (PFLOTRAN) to allow simulation of stream-aquifer-land interactions (Bisht et al. 2017), the coupled Community Land Model to ParFlow that is forced with the Weather Research and

Forecasting (WRF) model (Maina et al. 2020b), and the coupled ELM-FATES-ParFlow model for representing vegetation-hydrology interactions at the hillslope scale (Fang et al. in review). Such modeling capabilities will also enable a more complete picture of the integrated mountain hydrological cycle and, ultimately, how climate change will drive a cascade of changes that in turn impact decision-relevant outcomes. Given major computational advances in recent years, landscape-resolving, atmosphere-through-bedrock simulations are potentially achievable in the near term.

Fostering Interdisciplinary Exchange

The activities to improve observations and modeling will allow for a ModEx-based exploration of new opportunities to establish long-term datasets that will be necessary to provide the data for model improvements. Specifically, increased measurement frequencies, coordinated measurements across different atmosphere-terrestrial components, and continued improvements in measurement technology should lead to massive increases in data availability. These advances will enable more machine learning (ML) and artificial intelligence (AI) applications. Due to the complex linkages among climate, meteorology, hydrology, and ecology in the atmosphere-terrestrial interface, there is a general need to establish connections across disciplines involved in atmospheric and terrestrial science. Improving the interdisciplinary exchange can be fostered in the near term via workshops and targeted conferences. However, since interdisciplinary research needs to be a sustained effort, long-term support for such science is crucial. The foundation for an improved understanding among the disciplines should begin during an individual's education, and funding calls need to provide resources to sustain interdisciplinary research across various career stages.

4.2 Human-Atmosphere

The primary atmospheric components of mountain hydroclimate that directly interact with human systems are precipitation via water, energy, and agriculture resources; damage to infrastructure; and wildfires. Across spatial and temporal time scales, accurate predictions are required for stakeholders to make well-informed decisions.

Atmospheric rivers, in which strong water vapor transport occurs in narrow corridors, produce heavy orographic precipitation in many mid- and high-latitude mountain ranges, including the U.S. Sierra Nevada and Cascades. Despite being a critical source of water in many mountain regions, strong atmospheric rivers are also responsible for infrastructural damage due to flooding, mudslides, and rockslides (Payne et al. 2020). Water in other mountain ranges often depends more on precipitation from deep convection and/or winter storms. Downstream regions tend to be major agricultural areas susceptible to severe weather, such as flash flooding and hail facilitated by thermodynamic setups reliant on airflow over and into the lee of major mountain ranges (Houze 2012). These regions, such as the U.S. Great Plains, also rely on major rivers fed by precipitation over mountains such as the Rockies. Similarly, in tropical and subtropical regions, infrastructure needs to withstand and capture heavy orographic precipitation during the monsoon season, which is when nearly all annual precipitation falls. Many islands additionally depend on orographic precipitation in what would otherwise be very dry climates. Thus, planning of resilient societal water resource infrastructure critically relies on accurately predicting how climate change will affect a wide variety of multiscale precipitation properties over mountains and the downstream regions affected by mountains.

A key contributor to uncertain precipitation predictions is internal climate variability. Decadal variability is large over mountain regions, such as the western United States, and currently is difficult to predict with greenhouse gas warming mapped onto that variability (e.g., Stuivenvolt-Allen et al. 2021). This is problematic for water management planning, which requires 20- to 30-year time scale predictions. Another key contributor to uncertain predictions is future anthropogenic emissions that affect not only greenhouse warming but aerosols such as black carbon. Black carbon and dust generated by human-caused land degradation are deposited on snow where they absorb solar radiation and increase the rate of snowmelt and runoff. This effect can be as much as or more than that caused by greenhouse warming, leading to runoff earlier in the season as particles accumulate on the snow surface as the snowpack melts over time (Qian et al. 2015).

4.2.1 Human-Atmosphere Knowledge Gaps and Challenges

Primary human-atmosphere research gaps can be categorized in terms of whether they pertain to the influence of atmospheric processes in mountain regions on human systems or to the influence of human systems on atmospheric processes that impact mountain systems. With respect to atmospheric processes in mountain regions that affect human systems, the identified gaps focus on understanding how climate variability and change in mountain regions impact hydroclimate extremes, such as high precipitation events, drought, snow drought, and high-volume runoff associated with precipitation that occurs as rain rather than snow or that is due to rain falling on existing snowpack. With respect to the influence of human systems on atmospheric processes that impact mountain systems, workshop participants highlighted the role of anthropogenic aerosol deposition on snowpack, which can influence the timing and speed of snowmelt processes.

Precipitation Observations and Predictions Require Improvement

Fundamental understanding of how thermodynamic and dynamic changes in the atmosphere interact with one another to influence the characteristics of precipitation events is incomplete. Warmer air will hold more moisture, though precipitation will increase more slowly (Trenberth et al. 2003). However, it is not clear how circulations that advect and condense moisture will change across different regions, and yet understanding this is critical to understanding regional changes in precipitation (Swain et al. 2018).

Research suggests that as the global climate warms, many wet regions will get wetter while dry regions will become drier as large-scale circulations shift, though this may not occur over land regions (Greve et al. 2014). Warmer temperatures will also increase evaporation such that increasing precipitation does not necessarily decrease the probability of drought (Sherwood and Fu 2014). Increases in overall precipitation are likely to come in the form of more numerous extreme precipitation periods (Allan and Soden 2008), changes in the organization of precipitation systems (Tan et al. 2015; Feng et al. 2016; Prein et al. 2017) and the intensity of atmospheric river events (Huang et al. 2020), and potential super Clausius-Clapeyron scaling (Lenderink et al. 2017). A warming climate also causes shifts from snowfall to rainfall in mountain regimes where temperatures are commonly near freezing, but predicting precipitation phase and melt or accumulation remains difficult due to the importance of subtle changes in temperature and precipitation intensity.

The reflection of these combined possible changes onto any single mountain region remains mostly unknown due to limited and short-term observational records and insufficiently detailed models.

Outcomes will likely vary by region, highlighting the importance of feedback between cross-disciplinary scientists and stakeholders as decisions are made on how to design future infrastructure. In addition, understanding is incomplete for how large-scale atmospheric changes interact with local-scale feedbacks involving complex terrain features, turbulent flows, planetary boundary layer evolution, and couplings with land-surface fluxes of moisture and energy that dynamically change with vegetation and snow cover.

Internal Climate Variability is Poorly Predicted

Given limited availability of decadal and subseasonal-to-seasonal (S2S) data, it is not clear whether climate models can accurately capture S2S and short-range internal climate variability, which is significant in many mountain regions such as the western United States. From the data available, these models clearly have room for improvement. An additional complication is the role of temperature and land-surface changes in contributing to shifts in aridity and feedbacks to precipitation (Berg et al. 2016; Pendergrass et al. 2020). Not only do these processes impact drought and water availability, they also impact the probability of wildfires (Holden et al. 2018).

Anthropogenic Emissions are Unresolved Hydrological and Ecosystem Perturbations

Both local and remote emissions arising from human activities impact cloud, precipitation, and snowmelt processes in mountain regions. Agricultural soil disturbance generates dust, and fossil fuel usage produces black carbon in often distant upstream industrialized and urbanized regions. Such emissions can also occur locally in mountain regions because of forest management practices that influence wildfire regimes and thus wildfire-related emissions. Key research gaps include characterizing source emissions from such activities; measuring and modeling their transport and deposition through the atmosphere; and understanding how such emissions influence snow albedo, melt dynamics, and cascading effects on aquatic systems and emissions. In addition, wildfire-related emissions arise from complex interactions among direct anthropogenic influences with larger-scale climatic variability and change processes as well as ecosystem dynamics. Understanding how these drivers interact with one another to influence wildfire risk, burn dynamics, and emissions is also a grand challenge requiring a careful combination of observations and modeling. Finally, aerosol concentrations influenced by human and plant emissions may affect precipitation via direct radiative effects that alter the lower atmospheric temperature structure as well as indirect effects that suppress warm rain (Ramanathan et al. 2001) and intensify heavy precipitation and flooding (Fan et al. 2015). These processes remain poorly quantified.

4.2.2 Human-Atmosphere Research Opportunities

Science gaps and challenges limit the current predictability of interactions between atmospheric and human systems but also provide opportunities for advances.

Integrating Observational and Modeling Projects

Further combining multipronged observational campaigns with model development and testing within case study regions is a key strategy to address many science gaps and challenges given that so many processes interact across multiple scales within geographically specific contexts. One factor that may be missing from existing field laboratories that focus on relatively natural regions within mountains is a component that focuses on managed forests within mountain regions. This creates the possibility of conducting experiments or leveraging ongoing experiments with controlled management trials to disentangle anthropogenic land-use factors from atmospheric, ecosystem, and hydrological processes. For example, investigating what level of forest management and defensible space is required to have a meaningful impact on structure burning during wildfires requires interagency collaboration, studies focused on the wildland-urban interface and on structures, and planned research that leverages management activities. Identifying which mitigation strategies are suitable in the context of mountain hydroclimate extreme events is a critical opportunity in this area.

Cross-Scale Interdisciplinary Understanding

It is well known that internal climate variability up to time scales of decades dominates over forced variability from anthropogenic emissions; however, decadal and S2S predictability remain extremely limited. Even modest improvements could be hugely impactful in terms of guiding societal investments. More understanding of internal climate variability will improve models, but application of new statistical techniques, such as ML approaches for bias correction, ensemble-based uncertainty quantification, and extreme event predictability, may also have substantial impacts. Coupling longer-range predictive models that have simplified process representations and limited spatiotemporal resolution with detailed aerosol, cloud, surface, and human system models also has the potential to advance understanding, improve predictions, and guide better decisions.

4.3 Terrestrial-Human

As the world's water towers, mountain regions are critical for both *in situ* and downstream human activity (Viviroli et al. 2007). This leads to a strong interdependence between terrestrial and human processes over many mountain chains throughout the globe (Immerzeel et al. 2020). For example, human settlements, agricultural practices, and water use have developed over centuries and millennia around historically reliable upstream discharge flows (e.g., Himalayas). Furthermore, man-made storage in mountains (e.g., reservoirs) are strongly dependent on snowmelt and glacial melt to ensure higher agricultural yields and hydroelectric production. In contrast, anthropogenic impacts on mountain systems are leading to changes not only in mountain hydroclimate but also in land-use and land-cover change and groundwater processes (Biemans et al. 2019).

In mountain systems, many terrestrial-human processes span connections across multiple spatial scales. For example, groundwater reserves in valleys can be driven both by local recharge from rivers as well as groundwater recharge that takes place in high mountains (e.g., San Joaquin Valley; Wada et al. 2016). Water for agricultural purposes and human use can come from both these local to regional groundwater systems as well as from the riparian corridors that form downstream. Furthermore, upstream agricultural and livestock practices can directly impact downstream water quality and quantity. Figure 4.1 shows a satellite image of Boise, Idaho; this region's agriculture and water use are intricately connected to mountain hydroclimate.

These interactions between human and terrestrial processes over mountain regions lead to a complex interconnectivity between hydroclimate, agriculture, urbanization, environment, and energy needs that cannot be disentangled in regions where human populations are strongly dependent on mountain hydroclimate systems. These terrestrial-human interactions over mountain regions are tested under extreme events such as floods, droughts, and wildfires.

Fig. 4.1. Satellite View of the Boise, Idaho, Region. This region shows clear examples of multiscale terrestrial-human interactions through the use of mountain river discharge for agriculture along riparian corridors as well as for regional water supply. [Imagery ©2022 TerraMetrics, Map data ©2022 Google]

4.3.1 Terrestrial-Human Knowledge Gaps and Challenges

Three terrestrial-human grand challenges were identified: human-terrestrial interactions, wildfires, and extreme events that relate to major research opportunities.

Human-Terrestrial Interactions

Human-terrestrial interactions span multiple spatial and temporal scales between water and energy, carbon, and biogeochemical cycles. These interactions and complex feedback loops in mountain regions remain poorly understood, both qualitatively and quantitatively. First, there is a lack of data from physical and human interactions in mountain regions, and the complex topography of mountains challenges observational efforts, which creates a lack of data across terrestrial processes (e.g., land use, land cover, snowpack, river, land-surface interactions, and biogeochemistry of soil and rivers). Riparian corridors are critical components of the mountain hydroclimate system, and yet only poor data exist on the two-way interactions, and their representations in ESMs are practically nonexistent. Finally, human systems are most often represented as individual and local assets, but models largely ignore regional organization and cross-scale interactions. Human behavior needs to be generalized, and the science of human systems needs to be advanced as they are brought together with terrestrial processes for interpretation (Scanlon et al.,2017).

Wildfires

Wildfires are changing the predictability of both terrestrial and human systems, with punctuated and temporary changes in human systems. The impacts include loss of electricity transmission and substations, changes in electricity and water demands associated with the loss of infrastructure, and changes to ecosystem hydrology and biogeochemistry that can last years. Currently, there is conceptual research of complex interactions between wildfires and fuels as well as the wildland-urban interface; however, there remains an overall deficiency in observation and modeling capabilities (Aghakouchak et al. 2020).

Extreme Events

Extreme human-terrestrial events remain difficult to quantify and identify. Human systems are operated to minimize terrestrial extreme events, but tipping points are poorly understood or recognized. Similarly, the sequences of multiple events ultimately leading to extreme events are largely unexplored (Zscheischler et al. 2018). For example, a rain-on-snow event of an average snowpack can lead to an extreme event for human systems. Drought severity has often been measured by the local impact of droughts on human systems, although studies are emerging that define drought severity as impacted by the governance system (Hadjimichael et al. 2020). Understanding complex interactions between terrestrial and human systems requires developing new scientific methods (Reed et al. 2022).

4.3.2 Research Opportunities

The study of terrestrial-human interactions within mountain systems remains in its infancy; however, workshop participants outlined some of the many research opportunities within this area.

Human-Terrestrial Interactions

Topologies of human systems are emerging (Yoon et al. 2022; Brelsford et al. 2021); a specific topology of human-terrestrial system interactions would motivate future hypothesis-based research. This topology should integrate social scientists and communities of stakeholders to advance human system sciences in the context of Earth systems. Stakeholder communities are also an excellent resource to collect data across systems and scales. This topology could be started by cataloging existing datasets to understand benchmarks in observing and evaluating modeling approaches. Small-scale terrestrial-human field and laboratory experiments can help in the short term while the evolving topology further defines the needed observations across scales. For example, field greenhouses can be used to test how different emission scenarios or prescribed fires impact hydro-biogeochemical feedbacks. Experiments such as this have the potential to aid in developing management strategies to deal with carbon sequestration and water crises across drought-prone mountain regions. This specifically helps address pressing research questions to determine which mitigation strategies are suitable in the context of extreme events that influence mountain hydroclimate.

Near-term research opportunities include modeling exercises complemented by dataset extension. While there have been advances in further representation of human-terrestrial interactions in Earth-human systems (Voisin et al. 2013a; Yassin et al. 2019), there is typically a lack of coordination between human systems (Rouge et al. 2019), and the interactions between terrestrial and human systems tend to be driven by climate variability. Efforts in ESM parameterizations and representation of human-terrestrial interactions (riparian corridors and reservoir management) are expected to help with these new interactions. Efforts to build and organize datasets, including AI/ML-based dataset extensions that have integrated terrestrial-human data harmonized to the same spatial and temporal resolutions, should also help facilitate large-sample and generalization of interactions. Following this, the definition of extreme events associated with the interaction of terrestrial and human systems should advance.

The long-term vision consists of an array of modeling approaches of integrated human-terrestrial interactions across a range of scales for robust to nonstationary conditions. Experiments of fully integrated models, hybrid coupling, and storyline formats will allow generalizing model structures and parameterizations describing human behavior. This vision will benefit from citizen science and crowdsourced data as well as close collaboration with other agency efforts, such as those of the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and nongovernment agencies including the National Hydropower Association, for collecting data and capturing governance oflocal human system interactions.

Wildfires

Wildfire research is challenged by the fast changes in hydrological and human system responses and existing lack of predictability for their occurrences. Many observations encompass post-wildfire efforts that look at restoration advances with assumed indirect benchmarks such as streamflow. Human systems responses need to be better understood and human-terrestrial interactions need to be explored in pre- and post-wildfire situations using analog basins. Again, AI/ML dataset extensions might help in this endeavor. As data are key, scientists need to push boundaries and better integrate social scientists and community engagement to collect and analyze data across systems and scales and to catalog existing datasets to understand benchmarks in observing and evaluating modeling approaches. Although workshop participants focused on mountain climate with complex topography, they also included mountain climate on the U.S. high plateaus where urbanization is changing the foothills of the mountains as well as the wildland-urban interfaces. In the long term, participants envisioned enhanced predictability of the source and evolution of mountain forest wildfires through better understanding and modeling of triggers, both natural (e.g., lightning) and man-made (e.g., transmission lines and campfires), as well as associated mountain soil and vegetation conditions including forest practices and roads.

Extreme and Consecutive Events

In addition to wildfires, enhanced predictability of the source and evolution of floods, landslides, avalanches, drought, snow droughts, sediments loads and associated erosion, and stream thermal events can be achieved through better understanding and modeling of natural- and man-made triggers, initial conditions, and interactions between co-evolving terrestrial and human systems and associated consecutive events. Defining extreme events across terrestrial-human system interactions needs to go beyond typical engineering definitions such as percentiles and return periods. There is a need to work with human system operators to qualitatively understand the definition of extreme events in the context of impacts to human systems. This is also how consecutive events could be considered, which themselves might represent an extreme event. Even from a biogeochemistry perspective, an extreme event is most often monitored through human systems interest (e.g., river chemistry) and biodiversity. There is also a need to further invest in developing longer records to capture extreme events and define benchmarks. A challenge of terrestrial-human system interactions is that they co-evolve very fast. A hybrid of paleo data and/or synthetic data is needed to understand a range of system outcomes. In the long term, leveraging remote sensing of extreme events (e.g., satellite and airborne) over mountain regions is envisioned. This would help to generalize and extrapolate local information and address transferability of extreme events to different mountain regions for robust analytics in environments typically scarce in observations. Such an effort would also include exploration of synthetic datasets.

5. Crosscutting Science

5.1 Integrated Mountain Hydroclimate Variability and Change

Hydroclimate in mountain regions is among the most sensitive to changing climate and human system impacts. Shifts in climate will result in warmer conditions, changes in precipitation to include more extremes, and shifts in precipitation phase (e.g., from snow to rain), with implications for snow and seasonal water supply and water resource predictions. These changes in climate will impart complex and unknown consequences on water partitioning because of cross-scale interactions and processes across the atmosphere through the bedrock, ranging from continental- to watershed-scales and from subannual to decadal time scales. Improved process understanding within and across mountain ranges is needed to ensure that knowledge is transferred and that proactive adaptation strategies to these changes are considered now. Advances in observations and Earth system models (ESMs) require a balance of improved process fidelity representation and an ability to perform uncertainty quantification, with one overarching objective to determine the minimum but sufficient process representation to advance integrated mountain hydroclimate (IMHC) variability and change.

5.1.1 IMHC Variability and Change Knowledge Gaps and Challenges

Six grand challenges related to IMHC variability and change were identified: (1) modeling orographic precipitation, (2) vegetation feedbacks, (3) snow drought, (4) lack of spatial observations and cataloging of existing datasets, (5) uncertainties in modeling mountain hydroclimate, and (6) predicting future changes in mountain hydroclimate.

Modeling Orographic Precipitation

Seasonality, spatial patterns, and the structure of precipitation can vary substantially across mountain regions and within a given region. However, climate models are commonly too coarse in resolution to resolve complexity associated with orographic precipitation, land surface heterogeneity, and feedbacks between atmospheric and terrestrial processes. As a result, modeling orographic precipitation, particularly projecting future changes in the pattern and structure of precipitation, is a key challenge. Also unclear are the implications of changing precipitation for other hydroclimatic variables (e.g., snowpack, runoff, and terrestrial water storage), their trend and seasonality, and hydroclimatic extremes (e.g., flooding, drought, and wildfire) in future climates.

Vegetation Feedback

Key challenges for models at various scales are simulating process-level interactions between atmosphere and vegetation and determining how they feed back into regional hydroclimatic conditions and extremes. For example, it is not well understood how extreme events such as drought and wildfire can impact structural vegetation (e.g., vegetation patterns, distributions, and composition) and physiological vegetation feedbacks (e.g., soil moisture extraction and evapotranspiration) or how vegetation-soil moisture feedbacks at different scales may influence hydroclimatic variability across scales. For example, Maina and Siirila-Woodburn (2019) showed that post-wildfire changes to the landscape impact the surface and surface flow pathways of water via shifts in infiltration patterns and increases in snowpack accumulation, which affect water partitioning nonlinearly. Many studies confirm the dominant influence of fine-scale forest canopy characteristics (e.g., canopy density, structure, and its spatial arrangement) on snowpack dynamics and snow cover distribution, but the subpixel-scale representation of canopy is lacking in ESMs as well as models used for regional hydroclimate modeling (Mazzotti et al. 2020; Sun et al. 2022). Also, it is not yet understood what the threshold or tipping point might be for extreme events (e.g., drought duration and post-drought wetness) that cause irreversible changes or hysteresis in vegetation dynamics and related hydroclimatic processes. For example, a recent study by Peterson et al. (2021) found that the prolonged Millennium Drought occurring in southeast Australia induced changes in vegetation phenology. These vegetation changes resulted in irreversible shifts in watershed hydrological regimes that are characterized by a persistently higher evapotranspiration rate and a reduced runoff-to-precipitation ratio, even after the drought and despite wet and dry years.

Snow Drought

In mountain regions such as the western United States where seasonal snowpack supplies much of the downstream freshwater resources, snow droughts can have significant impacts on regional water availability and ecological and socioeconomic systems. Global warming is expected to exacerbate snow droughts, which are largely affected by storm tracks on seasonal to decadal time scales. There is a challenge in modeling and thus a lack of understanding of how snow drought may change in future climates. Understanding how internal variability of the climate system may influence future snow droughts is also lacking. Depending on the meteorological driver, snow droughts can be classified into warm snow drought (caused by above-normal warm winter temperatures), dry snow drought (caused by winter precipitation deficits), and combined warm and dry snow drought (Harpold et al. 2017; Hatchett et al. 2022). Recent studies (Rhoades et al. 2018; Musselman et al. 2018) suggest more frequent warm snow droughts in future climates as warming is expected to shift the precipitation phase from snow to rain. It is not yet clear how snow droughts caused by different climate drivers may change in the future and how they may impact downstream water availability regimes. The cascading impacts of multiyear diminished snowpack conditions are also poorly constrained (Siirila-Woodburn and Rhoades et al. 2021). With reduced snowpack in future warmer climates, there is an immediate challenge to predict seasonal water supply for mountain regions. A recent study (Livneh et al. 2020) shows that by late century (2070–2099), 83% of historically snow-dominated areas of the western United States will experience a decrease in the ability of using snow information to predict seasonal drought and streamflow, with lower-elevation coastal areas most impacted by warming.

Lack of Spatial Observations and Cataloging of Existing Datasets

Given the importance of snow processes for mountain hydroclimate and the fine-scale heterogeneity of snow cover and snow regimes, high-resolution, spatially comprehensive observations of snow (e.g., snow depth, snow water equivalent, snow density, and snow surface temperature) are crucial for better understanding and modeling the spatial distribution and regime of snowpack, particularly in forested environments where snow processes are strongly influenced by forest canopy. Despite the increasing availability of high-resolution spatial data such as NASA Airborne Snow Observatory (ASO) and LIDAR measurements, spatial observations of snow and canopy that span multiple years are still lacking for much of the mountain regions around the world, particularly at high elevations and in snow-rain transitional zones (Musselman et al. 2018; Sun et al. 2019). Co-located measurements of climate, canopy, and snow variables and catchment discharge are also largely lacking, limiting understanding of the control processes of snowpack dynamics and preventing parameterizations of snow processes, including canopy snow processes and subsequent impacts on surface and subsurface hydrology at the subgrid level in ESMs or hydro-terrestrial models. Additionally, there is a limited ability to rapidly collect data during extreme events, highlighting a major gap in process representation and understanding. A contributing factor to model data needs and requirements is that a wealth of data already exists but has yet to be fully curated, stored, quality assessed and controlled, and utilized because of a lack of data standardization formats and integration across similar datasets. The accumulation of underutilized data from past field campaigns points to the need for a shift in priorities that includes a focus on comprehensive data interpretation and analysis.

Uncertainties in Modeling Mountain Hydroclimate

A framework that respects the spatial heterogeneity and interactions between systems in ESMs, such as the Energy Exascale Earth System Model (E3SM), is needed for characterizing and quantifying the uncertainties. This is particularly important for modeling and understanding mountain hydroclimate with large gradients in topography, temperature, precipitation, and vegetation cover. Substantial uncertainties can be attributed to (1) the choices and downscaling approaches used for global or regional climate models, (2) model resolution and representation of land-use and land-cover spatial variability and their interplay with terrestrial processes such as snow and soil-water processes, and (3) model representation of feedback between atmospheric and terrestrial processes. Additionally, uncertainties exist given human system feedbacks (see Sections 2.3, 3.2, and 3.3), including scientific and modeling gaps between the anthropogenic activities around adaptation and mitigation strategies. Examples include considerations of reservoir dynamics and operations, hysteresis effects, occurrence of reservoir dead pools, and the human response to system perturbations like the “miracle spring”—prolonged drought unexpectedly mitigated by a significantly large amount of spring precipitation.

Often in models, the choice of certain processes and scales comes at the expense of other critical processes, with unknown and unquantified uncertainty resulting from such exclusions. With multimodel ensembles, advanced model couplings, and multiscale model intercomparisons, there are new opportunities to understand the resolution required to simulate different types of key processes or extremes and inform subgrid parameterization or process refinement for ESMs. Further, this high-resolution information should be used in coupled human-ESMs to understand feedbacks and tipping points in these systems. For example, coupling of variable-resolution ESMs with integrated hydrological models allows for the joint consideration of thermodynamic and dynamic shifts in a projected climate while also explicitly modeling hydrogeological responses in above- and belowground water energy balance at decision-relevant scales. Bedrock-through-atmosphere coupling of process representation and feedbacks, while still in its infancy, represents the type of “hierarchy of systems” with potential to be aided by work in new artificial intelligence (AI) and machine-learning (ML) techniques, as highlighted below. For instance, AI emulators provide an opportunity to introduce simulations of complex subsurface flow, biogeochemistry, or wind patterns at various scales.

Predicting Future Changes in Mountain Hydroclimate

Complexities in the spatial and temporal patterns of mountain hydroclimate changes make the predictability of ongoing and future change difficult. Studies are needed to quantify the characteristics of these changes. For example, signatures of extremes (such as very dry versus very hot years) can be used as indicators of potential change. However, given nonlinearity and a lack of natural analogs of expected changes, reliance on physically based models will be important to make accurate and informed projections. Considerations of regionally specific characteristics (e.g., the response of land use and land cover) will be important to quantify how one region will respond to different levels of change. These challenges point to a need for a comprehensive sampling of extremes, large ensembles, and baselines of observed and simulated historical data for comparison.

5.1.2 IMHC Variability and Change Research Opportunities

Regionally Refined Modeling and Dynamical Downscaling

The large interannual variability in mountain regions makes disentangling signal from noise difficult and suggests a need for large ensembles of climate model simulations. While several such ensembles are now available publicly and have contributed significantly to an understanding of the climate system and its response to climate change (Deser et al. 2020), the grid spacing employed in these simulations (typically around 110 km) is insufficient for resolving topographic and meteorological features in mountain regions. High-resolution climate simulations (Roberts et al. 2018), which would enable a more accurate representation of topography, (extreme) weather features, and atmosphere-land surface interactions, are needed to address this gap. For example, as shown by Rhoades et al. (2018), mountain snowpack is generally convergent in atmospheric models when grid spacing is around 14 km, but higher resolution still is needed to capture mountain valleys and other features of mountain meteorology. However, the high computational cost of such simulations currently precludes their development. To overcome this problem, targeted ensembles using technologies such as regional refinement or dynamical downscaling should be developed and made available to the scientific community for analysis (Gutowski et al. 2020; McCrary et al. 2022).

Comprehensive AI/ML Representation of Mountain Systems

AI and ML has been shown to be immensely useful in identifying relationships in systems where processes are not well constrained. AI emulators of hydrological, ecological, or biogeochemical processes in mountain regions could be used to improve representation of these processes in regional or global ESMs. For instance, recent developments have led to improved representations of the integrated hydroclimate system, including streamflow (Duan et al. 2020), snow water equivalent (Meyal et al. 2020), groundwater (Sahoo et al. 2017), and wildfires (Wang et al. 2021). Some studies have shown that AI/ML systems can outperform process-based models in terms of accuracy (Kratzert et al. 2019). AI-based systems are also being used for downscaling of climate information from coupled climate models (Vandal et al. 2019). Simultaneously, efforts related to explainable AI have made it easier to understand which relationships are being identified within these systems and thus have made more transparent the “black box” of these AI-based models (McGovern et al. 2019). Nonetheless, new methods and model designs are being continuously explored and applied to problems in mountain regions. When combined with adequate datasets, AI/ML representation advances the full potential of ModEx approaches.

Data Cataloging and Metrics and Diagnostics for Evaluating Models and Cross-Region Comparisons

With new observational datasets coming online, deeper analyses being performed with existing data products, and more simulations underway at the resolutions needed to resolve mountain processes, improved cataloging of these datasets (e.g., through a project such as obs4MIPS; Waliser et al. 2020) has the potential to accelerate scientific discovery and enable more comprehensive model evaluation. The accumulation of data from past field campaigns presents a major research opportunity to curate spatially and temporally complete datasets in existing catalogs across the globe. By leveraging all existing datasets and simulations (both past and present), there is further opportunity to develop and deploy new metrics and diagnostics for comprehensive evaluation of climate modeling systems and terrestrial processes that are key to understanding regional hydroclimate. Research efficiency and impact would likely be greatly amplified by expanding data harmonization and building out data repositories to include data processing and analysis tools.

Metrics that address cross-region similarities and differences at multiple scales should also be developed, such as those that quantify the dominant mechanisms of regional hydroclimate and/or measure the sensitivity of hydroclimatic regime to changing climate. These metrics should potentially be used as references for evaluating transferability of models or knowledge across regions. To give one such example, the snow model intercomparison project (ESM-SnowMIP; Krinner 2018) has recently explored metrics for evaluating the performance of various mountain snowpack models. Comprehensive model evaluation using multiple metrics and all available observational datasets can allow the identification of correlations between model biases and upstream drivers of those biases (Xu et al. 2019). Initiatives such as Coordinated Model Evaluation Capabilities or the Model Diagnostics Task Force (Maloney et al. 2019) should also be leveraged to improve interoperability between model evaluation software tools. To advance extreme event capabilities, there is an opportunity to revisit underutilized data from past field campaigns, couple those with novel state-of-the-art modeling, and develop rapidly deployable observational campaigns, all of which will be instrumental in analyzing extreme events.

Bedrock-to-Atmosphere Process Understanding and Modeling

Mountain processes extend from the deepest aquifers through the land surface, troposphere, and into the stratosphere. Comprehensive modeling of the system from bedrock through atmosphere would enable disentangling relationships that exist among processes at all levels while conserving invariants such as water mass. A hierarchy of modeling systems should further be developed to incorporate observations at all scales, such as those from the Atmospheric Radiation Measurement (ARM) user facility's SAIL campaign (Feldman et al. 2021), the ASO LIDAR (Painter et al. 2016), and other observational campaigns that have or will be launched. For example, coupling of variable-resolution ESMs with integrated hydrological models allows for the joint consideration of thermodynamic and dynamic shifts in a projected climate while also explicitly modeling hydrogeological responses in above- and belowground water energy balance at decision-relevant scales (Maina et al. 2022). This hierarchy of systems could be aided by work in AI/ML systems, as highlighted above.

Novel AI/ML, hybrid, and lumped modeling approaches that combine bedrock-through-atmosphere remote sensing and field-based data layers to improve conceptual model development have incredible potential to advance understanding beyond what mechanistic modeling is currently capable of providing (i.e., Wainwright et al. 2022; Chaney et al. 2018). For example, in the Upper Colorado River Basin, decadal declines in river nitrate have been observed (Newcomer et al. 2021). Since river chemistry is a complex function of highly nonlinear interacting hydrological, biogeochemical, and ecological factors across bedrock-vegetation-atmosphere interfaces, model limitations currently preclude a predictive understanding of causal factors contributing to observed decadal nitrate declines. AI/ML, hybrid, and lumped models have been shown to be immensely useful in identifying causal relationships in systems where process representation is nonexistent or poorly constrained (Maavara et al. 2021).

Identify Region-Specific Mitigation and Adaptation Strategies for Future Extremes

Large interannual and intra-annual hydroclimatic variability in mountain regions can make planning for extreme events, such as prolonged drought or flooding, difficult. In conjunction with local stakeholders and policymakers, efforts are underway to identify optimal mitigation or adaptation strategies. However, many questions remain about how mountain regions can best adapt to a changing climate, particularly considering complex intersectoral dynamics and future uncertainty. For example, it is unclear how prolonged drought and reservoir operations will impact the capacity to generate electricity at hydroelectric dams (Szinai et al. 2020). Also unclear is the best strategy for managing montane forests amid increased wildfire risk and climatic shifts (Keenan 2015) and whether legal frameworks related to water rights can be managed when water supplies are insufficient (Schwarz 2015). With substantial spatial heterogeneity in hydroclimatic extremes and land surfaces, management strategies for future extremes need to be made at decision-relevant scales that are much finer than ESM grid resolution (> 4 km). With multimodel ensembles and multiscale model intercomparisons, there are opportunities to understand the resolution required to simulate key processes for different types of extremes and inform ESM subgrid parameterization or process refinement. Further, this high-resolution information should be used in coupled human-ESMs to understand feedbacks and tipping points in these systems.

5.2 Atmosphere-Terrestrial-Human Interactions

A major aspect of actionable science in the atmosphere-terrestrial-human (ATH) interactions domain is to identify and minimize biases in model simulations. The key science question is how best can the biases, real means, variability, and extremes in mountain hydroclimate be understood and used to improve simulations of means and extremes spanning days to centuries? The large spatial extent of model simulations in mountain regions poses significant challenges to existing observational systems and reduces the availability of actionable information at fine scales. Extreme precipitation and associated landslides and debris flows were identified as important processes at the intersection of atmospheric, land, and human systems. Improved operational forecasts and gridded precipitation estimates are needed to help resolve current model variability for event prediction with short lead times. The development of parameterizations that account for subgrid-scale processes such as turbulent flows, flow interaction with topography, and snow redistribution and evaporation, was highlighted as a priority. Additionally, simulating mountain environments beyond their natural state by including the effect of human activities on the hydroclimate was identified as an urgent research topic.

5.2.1 Atmosphere-Terrestrial-Human Knowledge Gaps and Challenges

Workshop participants identified three knowledge gaps that relate to relevant research opportunities: (1) determining priority landscapes, (2) understanding shifting extremes, and (3) modeling ATH interactions.

Priority Landscapes

Mountain regions are characterized by strong gradients in temperature and precipitation as well as high variability and extremes. Also, the human settlement of mountain regions is heterogeneous, with population concentrations in the more hospitable zones. Because of these factors, climate change and shifting extremes in mountain regions have stronger and less predictable impacts on coupled atmosphere-land-human systems than impacts from flatlands. To the extent that society prioritizes natural ecosystems as potential resources for carbon capture and storage to mitigate ongoing climate change, mountain watersheds in the western United States will be important for managing long-term carbon storage. Mountains are challenging regions for decision-making and risk management because of the overlay of current species distributions with steep and shifting climate gradients in landscapes that are already a complex mosaic due to past and current management practices and natural disturbances such as wildfire and insect damage. The biogeography of forest distributions, growth rates, and susceptibility to disturbance is complex and only partially understood in these complex environments, and human intervention in the face of ongoing shifts in means and extremes of climate is an uncertain endeavor.

Shifting Extremes

Flooding along the Yellowstone River in Montana recently (June 2022) provides an example of the amplification of climate change impacts on coupled systems that can occur in mountain watersheds. Extremes in snowpack, temperature excursions, and precipitation have combined with economically vital development patterns that follow the main river channel, producing a flooding event that has brought transportation, commerce, and tourism to a standstill and damaged critical infrastructure that will take years and many millions of dollars to repair.

Extreme climate gradients and high variability across time scales from days to decades make adequately measuring and characterizing mountain hydroclimates very difficult. An important challenge for interactions with human systems is knowing how much measurement capability to deploy and where to place it. Many important locales are simply inaccessible for instrument deployment or data collection (such as steep ridges, remote high-elevation plateaus, and wind-swept divides). Remote detection instrumentation (e.g., radar) is often obstructed by terrain, and airborne and spaceborne remote-sensing platforms suffer from frequent cloud cover and the challenges of variable snow cover in image interpretation.

Compounding extreme events, such as snow droughts and wildfire, are examples of critical research gaps in mountains because of their direct relationships and vulnerability to changing climate conditions. This challenge arises because both wildfire conditions and snow drought are largely affected by storm tracks on seasonal to decadal time scales. The mechanisms by which wildfire is exacerbated by snow drought and antecedent soil moisture conditions, and how wildfire can then tip soil hydro-biogeochemistry toward new steady states and biomes, requires research across the coupled groundwater-soil-vegetation continuum. Along mountain foothills, the expansion of wildland urban interfaces is a direct anthropogenic influence on wildfire risk, burn dynamics, and emissions, all of which require a careful combination of observations and modeling to address.

Modeling ATH Interactions

Modeling ATH interactions remains a significant research challenge. An example of interrelated ATH interactions for wildfire in response to evapotranspiration, precipitation, and human systems is provided here as a use case highlighting the integrated research required to support future IMHC activities. Modeling these coupled conditions in mountain systems motivates the need for new advancements in modeling and observational platforms.

Evapotranspiration. Measuring, modeling, and benchmarking evapotranspiration remain significant research challenges. Because evapotranspiration fluxes highly depend on terrestrial, human, and atmospheric interactions, a coupled bedrock-vegetation-atmospheric model would be required to benchmark observational datasets and conduct modeling experiments under land-management activities (e.g., forest management) or wildfire.

Precipitation. Modeling and measuring orographic precipitation, including the pattern and structure of precipitation across mountain topography, is critical because it is a direct controlling factor on evapotranspiration and wildfire. The discrepancy between the scale of precipitation observations and the scale of simulations further challenges an accurate representation of evapotranspiration fluxes in land-atmosphere modeling. Furthermore, considering the role of wildland-urban interface expansion in mountain systems, the feedback of this expansion on both vegetation-driven evapotranspiration and local atmospheric forcings (e.g., changes to surface energy balance and water use) will challenge current ATH modeling and observational capabilities.

Human Systems. Incorporating human systems into ESMs is still in its infancy when it comes to responses to evapotranspiration, wildfire, and precipitation changes across mountain regions. Models are needed that include human and multisector dynamics enabling actionable science and decision-making and that properly represent human processes as forcing mechanisms. Long-term observational platforms and models that include human–multisector dynamics that adequately capture the diversity of human systems will be critical to these models' success in predicting before and after wildfire.

Wildfire. Mountain wildfire is the perfect use case of the necessary integration of ATH interactions across scales. Wildfire plays a key role in landscape hydrological and biogeochemical processes because of interactions and changes across the soil-vegetation continuum. These changes include vegetation loss and shifting evapotranspiration, changing soil hydraulic parameters, and introduction of new solutes and nutrients from combustion byproducts. An important factor in whether wildfires can impact hydrological partitioning is post-wildfire precipitation frequency, magnitude, and duration (Maina et al. 2020a; Murphy et al. 2015, 2018).

A key challenge for models is simulating process-level interactions and feedbacks between wildfire, atmosphere, vegetation, and subsurface biogeochemistry. Additionally, inclusion of wildfire-related impacts on critical model parameters, such as porosity and hydraulic conductivity, currently require models to pause to incorporate new parameters associated with wildfire-related changes. Given that wildfires are increasingly occurring at the wildland-urban interface, models must account for human-induced wildfire ignitions and spread as well as anthropogenic chemicals (e.g., phosphates and nitrates) that greatly impact terrestrial biogeochemical cycles. Observational campaigns and models are currently not equipped to respond to the rapid onset of wildfires. As such, new ModEx-style network-of-network groups and rapid-response activities will be necessary to quickly leverage capabilities across communities to achieve measurable progress in observing and predicting mountain hydroclimate response to wildfire.

Since the assumptions used for models are becoming less valid due to changing aerosol emissions (e.g., from increasing wildfires) and warming conditions that alter the melt processes in the mountains, there is an immediate need for new observations that can be used to calibrate and update model process representations. At the same time, there is a need for improving predictions and risk estimates of compound extreme events across scales. Examples include prediction of simultaneous droughts and heatwaves or wildfires followed by intense precipitation. From a stakeholder engagement perspective, the lack of sufficient integration of climate and weather services was identified as a limiting factor. Critical decisions, communications, and response by members of the public can be impacted by this lack of proper data integration.

5.2.2 Atmosphere-Terrestrial-Human Research Opportunities

Many new opportunities emerge in the context of ATH interactions:

- Learning from heterogeneity studies in low-relief terrain as physical forcing and thermal forcing interactions are considered in mountain terrain.
- Combining existing and new subgrid capabilities of models such as the E3SM Land Model (with a topography-defined subgrid) with an approach that recognizes the natural organization of watersheds (including nested watershed analysis)
- Integrating a dynamical high-resolution approach (e.g., HyTEST) with a statistical approach (e.g., Daymet) to produce a more reliable historical hydroclimate database, which is useful for quantifying impacts and extremes and for forcing of hydrology and impact models.
- Acquiring and curating data to improve the forecast chain and uncertainty quantification.
- Including bedrock-through-atmosphere process representation of ATH interactions across the range of local and global models
- Utilizing a wildfire use case as a scenario to benchmark models and observations.

From a data integration perspective, using and acquiring new aerosol, precipitation, and snowpack measurements to update and improve retrievals and predictive models should be prioritized. High-resolution, spatially comprehensive, and long-term observations of snow, in addition to long-term datasets that establish ecosystem steady states before extreme events, are crucial for better understanding and modeling the spatial distribution and regime of snowpack that drives extreme phenomena. Rapidly deployable observational campaigns that respond to extreme phenomena at times and places where they occur will be required to gather critical extreme event–scale data.

Furthermore, opportunities exist for improving uncertainty quantification for compound events via Big Data mining and improved simulations coupled with measurements. Improving such models to guide decision-making will require improving the entire forecast chain, which begins with weather and future weather inputs to hydrological models that then provide the basis for risk dissemination and mitigation strategies. Much work will be needed to examine mitigation strategies in the context of climate change and extreme events using models as forecasting tools and observational and experimental approaches to develop novel and potentially transformative mitigation strategies. An example of this type of co-beneficial experimental research would occur if mountain forest management activities were used to address science questions related to extreme event thresholds on hydro-biogeochemistry that had co-benefits for improving the ability to mitigate the impact of extreme events on the hydrological cycle.

Nontraditional observational campaigns create the possibility to conduct experiments or leverage ongoing experiments with controlled management trials to disentangle anthropogenic land-use factors (human) from atmospheric and terrestrial influences. Additionally, making code more transferable between modeling systems is a necessary next step. For instance, many high-resolution models that can simulate mesoscale processes in mountain regions have simple land-surface schemes, while coarse-resolution ESMs typically have much more advanced land-surface models but struggle to simulate fine-scale processes.

5.3 Societal Connections and Implications

Regarding societal connections and implications, major concerns are centered on two subjects: risk and uncertainty. In particular, the perception of risk and risk tolerance, such as quantifying risk in the decision-making process, is of the utmost importance. The main reason for targeting risk lies in the current challenges to (1) relay uncertainty to end users and (2) make decisions under untold or unquantified uncertainty. Nevertheless, since uncertainty will persist in current modeling tools, the ability to answer the two questions of how it is best communicated and adapted to stakeholders and how it varies with different sectors should be a central challenge and opportunity for DOE to invest in over the next 5 to 10 years.

The societal sectors affected by the current gap in addressing and communicating uncertainty are (1) water management, including irrigation and groundwater pumping; (2) forest management, including prescribed burns and thinning as well as landscape management; (3) tourism, which is affected by snowpack change and extreme floods and droughts; and (4) anthropogenic local aerosols, including sulfate, black carbon, dust, and biological particles. These sectors and their associated issues affect all mountain regions in the world, particularly in developing countries where water-related conflicts and hazards are acute and legal mechanisms for resolving resource-related conflicts are not well developed. For the developed world, collaboration is equally needed to make sure that knowledge and models are transferable to different regions and different water economies. In the United States, workshop participants suggested priority regions that include the Colorado River Basin, California and Sierra Nevada, and the Great Salt Lake, which has displayed signs as an emerging threat due to rapid drying. Current tools also are limited in that U.S.-developed hydrological models are biased toward U.S. conditions and are difficult to apply directly to other continents.

As Fred Liljegren, late manager of the U.S Bureau of Reclamation's WaterSMART program once said, "If (your forecast) can provide 20% of confidence, I will take it! 20% is better than whatever we are doing, which is pure guessing." It was 2013, the same year the much-cited Colorado River Water Supply and Demand Study was released, which outlined what future water imbalance might look like through 2050. In hindsight, the simulated water supply missed the low-frequency variability and associated prolonged drought in the historical record, and the most recent (2020-21) drought was worse than anything projected by those climate-hydrological models. As the ongoing drought has impacted the reliability of the Colorado River system to meet water allocation agreements and hydroelectric power generation targets, future rising temperatures and shifting precipitation from snow to rain could make streamflow harder to predict and water resources less reliable, and any precipitation increases that might occur would likely be offset by the impacts of warming temperatures. The key to address uncertainty is developing decadal prediction as the middle ground between end-of-the-21st-century projection and seasonal prediction.

5.3.1 Societal Connections and Implications Knowledge Gaps and Challenges

Two knowledge gaps were identified that relate to relevant research opportunities: (1) uncertainty in water supply projection and (2) dealing with risks that shift with "initial condition" of forecast.

Uncertainty in Water Supply Projection

Under the projected future climate in which the evaporative demand of the atmosphere will increase and precipitation will consequently shift in mountain regions from snow to rain, there is a need to understand the relationship between water supply and hydroelectric power production. This key connection stems from the uncertainty in climate model simulations of the processes that drive low-flow conditions and their likelihood of occurrence in the future. Aiming for the 2- to 5-year time horizon, for example, the U.S. Bureau of Reclamation's Colorado River (CR) operations currently use three types of forecasts: CR Midterm Modeling System, CR Streamflow Forecast Testbed with the University of Colorado–Boulder, and Temperature-Informed Streamflow Projections with the National Center for Atmospheric Research (NCAR). All these forecasts produce a weighted projection of Lake Powell inflows to decrease by another 10% in the next 5 years, but the uncertainty is still large. Another example is an experimental decadal projection system of CR water supply that was developed by Utah State University. This system incorporates the recent downturn but projects an overall increase, as shown in the 2013 Colorado River Water Supply and Demand study, despite stakeholder concerns over the system's unquantified reliability and functionality (U.S. Bureau of Reclamation 2012). At the state level (e.g., Utah), the uncertainty in water supply projections for rapidly developing metropolitan areas highlights the challenge in trying to predict the state's water supply without the ability to fully account for water allocation of the Great Salt Lake's tributaries. Consequently, there is difficulty in determining how to respond to a recent New York Times article that states, "as the Great Salt Lake Dries Up, Utah Faces An 'Environmental Nuclear Bomb'" (Flavell 2022).

Dealing with Risks that Shift with "Initial Condition" of Forecast

The risk from uncertainty in everyday hydrological operations can be illustrated in Fig. 5.1, which shows Lake Powell's water level projection, as initialized in December 2021. An enormous spread quickly emerges from the Year 2 forecast and expands to exceed the full range of standard deviation in the historical data in Year 5. A similarly large spread in the water level of Lake Mead was also seen (figure not shown), albeit with a more gradual error growth than the forecast for Lake Powell. This challenge in large forecast variability was attributed to the initial condition of the input feed(s) into the forecast model. Streamflow models take into account considerable details, including fine-scale and rapidly changing surface and atmospheric conditions. Utilizing too much detail to predict too far into the future ruins a forecast. This is a lesson meteorologists learned a long time ago while developing numerical weather prediction in the 1950s. A change in the initial conditions alters the forecast, and so having flawed initial conditions produces an impractical range of variability and errors, including the huge variability and errors for Lake Powell.

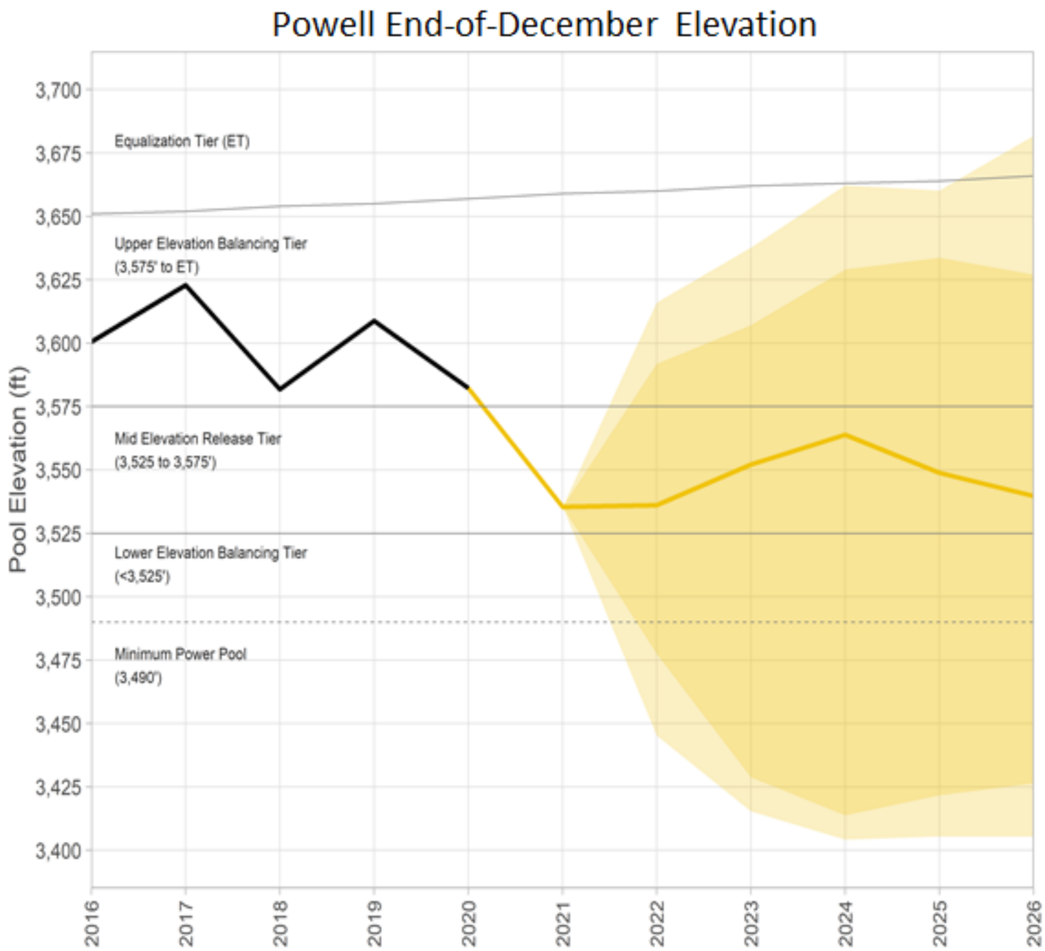

Fig. 5.1. Projections of Lake Powell Water Level by Resampling 1988 to 2019 Natural Flows (Stress Test Hydrology). In contrast to the June 2021 projections, these results do not include Upper Basin Drought Response Operations beyond 2021. The range shown in this figure may not be representative of the full range of possible conditions that could occur with different modeling assumptions. [Courtesy U.S. Bureau of Reclamation, www.usbr.gov/lc/region/g4000/riverops/crss-5year-projections.html]

To remedy this projection of long-range water supply forecast, a "get-by" solution might involve reducing the hydroclimatic factors that affect the near-future (5- to 10-year) change of a large mountain river system to forecast its water supply. Examples include the Colorado River decadal prediction system (Chikamoto et al. 2020) and statistical modeling (Plucinski et al. 2019) that resulted from the DOE-funded HyperFACETS project and Pacific Northwest National Laboratory's Metric-Guided Model Development (U.S. Bureau of Reclamation 2021). The numerical prediction framework of these models identifies the most important factors from the ocean-atmosphere-land coupled systems that affect the time-mean streamflow (e.g., annual), and only uses those factors to predict the averaged streamflow. This approach is fundamentally different from simulating and forecasting the daily or weekly streamflow with everything physically possible and then averaging the forecast streamflow for the next 5 years; the latter approach would accumulate errors rapidly, making the uncertainty too large to be useful.

Important questions associated with risk, decision-making, and adaptation are involved in understanding how the length of decision-making determines the tools used and how those tools vary across time scales.

- *Risk* — Knowing how well the risk of future states can be estimated after the (forecast) system shifts strongly in one direction (e.g., with reservoirs at new extremely low values) is challenging. In addition, there is a need to understand whether current risk estimates adequately account for the new state of the hydrological system. Also, issues associated with communicating risks to stakeholders from different sectors need to be recognized and decided upon.
- *Decision-making* — It is unclear how and where dam operators and water managers place confidence in climate services that either involve or provide long-range climate forecasts. In addition, there is a need to understand the optimal spatial variability in observations (desired versus reality) and the representativeness of landscape processes that should be considered for models.
- *Adaptation* — The ideal length of decision-making is unclear as is how tools should be chosen that vary across time scales. Stakeholders routinely face these common questions without a playbook of answers, and consequently, universally seek answers from the scientific community.

Expanding Instrumentation: Adding Surface Measurements

Reducing forecast errors also requires quality input data for models. Stakeholders view the installation of more observations across the western United States and accurate monitoring of snowpack as vitally important. High-elevation automatic weather station (AWS) installations remain rare because of the combined challenges of difficult access and harsh conditions. Existing AWS data, however sparse, serve to improve understanding of critical atmospheric and climatic processes as well as ground-atmosphere interactions in the context of local catchments, regional hydrology, and the high-mountain cryosphere.

Most stakeholders make decisions based on existing conditions derived from *in situ* observations plus their institutional knowledge. Forest management has engaged in increasing the coverage of weather stations to monitor and mitigate wildfire danger (National Wildfire Coordinating Group 2019). Stakeholders also urged the expansion of rugged, low-power measurement systems for timely monitoring in snowy climates. Preferable observation systems will measure snow depth, snow-water equivalent, air temperature, relative humidity, and wind speed and direction. Such data are useful for displaying current weather conditions, identifying snow-making conditions, forecasting spring runoff and summer water availability, and modeling avalanche conditions. One solution is to promote the installation of regional or state-operating weather monitoring networks to observe the environmental variables unique to the state, as was reported by the National Public Radio on March 15, 2022 (Eggers 2022).

5.3.2 Societal Connections and Implications Research Opportunities

Uncertainty in Water Supply Projection: When can the Colorado River be Relied on Again?

An extended and potentially skillful projection of water supply can be developed by combining the effects of ocean precursors and long-term climate projections. The major task lies in identifying observed long-term climate change components because the current generation of climate models still exhibits large biases and deficient physics schemes.

Model development needs stakeholder engagement. Technology aside, to strengthen stakeholder involvement in interpreting model forecast evaluation and its application, scientists need to engage effectively in “co-production”—or advancing science together with stakeholders to meet real needs. To motivate co-production between stakeholders and scientists and improve understanding of the coupled human-hydrology system, efforts focus on identifying how climate data are used in practice and where there is outstanding need. Co-production discussions subsequently inform which fields and processes are needed to address gaps, and they allow scientists to formulate metrics that enable stakeholders to understand model and dataset performance. Co-production can seek to identify which processes are most important for ensuring model performance and investigate the relative importance of other external forces (e.g., greenhouse gas emissions, water use, or land-cover change). Past research has indicated that such added understanding frequently motivates further questions related to model credibility and facilitates a continuous cycle of engagement (Jagannathan et al. 2021).

Over the next decade, DOE could benefit from its investment in hydroclimatic research and analysis and be recognized among stakeholders and scientists as a pioneer in knowledge co-production. Use of co-production processes would improve the actionability and decision relevance of hydrological prediction research by iteratively refining research questions, objectives, methods, and deliverables. This could be done by flexibly deploying teams of stakeholders and scientists in working groups that would iteratively collaborate on specific research challenges and deliverables. Examples follow.

One co-production research project that addresses the risk and uncertainty issues plaguing long-range water supply forecasts involves identifying the long-term climate change component and model biases in simulating hydroclimate processes in the Upper Colorado river basin. This approach isolates the internally generated climate variability from the radiatively forced component and adjusts the model biases involved in the future climate projection (Morgan et al. 2020). From a similar analysis, researchers can then estimate the ocean-induced multiyear drought components in the current and future climate conditions and apply the outcomes to develop multiyear and long-term water supply forecasts (Chikamoto et al. 2020). Another example is from a team of climate scientists and a group of Colorado River water managers who worked together to explore storyline events such as “miracle spring” high-precipitation events that unexpectedly saved a water-deficit year (Pokharel et al. 2021b). Their efforts included how to define and predict the elusive miracle. Within these forecasts, scientists and stakeholders could work together and assess plausible warmer climate projections to understand what might happen to seasonal or multiyear streamflow (and from there, hydropower production) under different conditions. Scenarios might include, for example, when the amount of snowpack accumulation decreases and the timing of peak snowmelt shifts earlier in the water year or when low-to-no snow conditions persist for decades at a time. By working routinely with water management personnel (through DOE sponsorship), reservoir storage (surplus and deficit) behavior can be captured as a function of inflows and demand (current and projected). The minimum active storage pool can then be used as an operations guide to estimate supply-demand imbalances and subsequent climate risks.

Risks that Shift with “Initial Condition” of forecast: When Will the Great Salt Lake Go Dry?

Depleting lake water of the Great Salt Lake amid the recent drought has spurred media coverage since 2021. The New York Times reported that “climate change and rapid population growth are shrinking the lake, creating a bowl of toxic dust that could poison the air around Salt Lake City” (Flavell 2022). The Weather Channel says, “Great Salt Lake in Utah is projected to drop to a new record low this year after hitting a record low last year” (Bonoccorso 2022), and CNN announced “Great Salt Lake is shrinking fast. Scientists demand action before it becomes a toxic dustbin." (Kafanov et al. 2021). Recently, a local politician's proposal made national headlines "Desperate Lawmakers Discuss Piping Ocean Water to Fill Great Salt Lake" as a drastic solution to save the lake (Taft 2022).

While the lake itself has significant ecological and environmental impacts, few people understand that it serves as the fuel gauge for underground water storage. About 80% of Utah's water use comes from agriculture, and 80% of the agriculture irrigation uses groundwater. At the decadal time scale, the Great Salt Lake elevation change goes hand in hand with northern Utah's groundwater fluctuation (Hakala 2014; Masbruch et al. 2016) and the Colorado River water supply (Wang, S.-Y. et al. 2018), making it a vital indicator for the intermountain region's subsurface water resource. Prediction of the Great Salt Lake's future has been attempted using statistical methods (Gillies et al. 2015) but has not been addressed with an integrated hydroclimatic modeling approach, highlighting this topic as a priority for DOE's future research.

The only way for humans to modify the natural source of water and shift initial conditions is through weather modification techniques, such as cloud seeding (wintertime orographic glaciogenic precipitation enhancement). Various western states have been conducting cloud seeding operations for decades in hopes of gaining more water during droughts (Williams 2022). While seeding orographic clouds can lead to a quantifiable increase in precipitation, recent research has suggested that high-resolution weather models and complex statistical techniques can be applied to evaluate the effectiveness of cloud seeding programs, meaning the future could be a very prosperous time for seeding operations (Tessendorf et al. 2015). Scientific investigation involving stakeholder participation and engagement has occurred in Wyoming and Utah (Pokharel et al. 2020) through collaborations with local water conservation districts.

Despite the popularity of cloud seeding, its effect on increasing winter precipitation remains elusive and scientifically uncertain. Given this sustained popularity and that most electric companies sponsor cloud seeding (e.g., Idaho Power and Pacific Corp.), it is important for DOE to sponsor scientific exploration to quantify the effect and uncertainty of cloud seeding occurring in the western United States. Ground-based cloud seeding programs use generators that release microscopic particles into clouds to act as a nucleus for ice crystals to form. Because this process works best once those clouds reach a mountain barrier, where rapidly lifting and cooling winds help turn clouds into snow, the precise location of these generators is critically importance. Without a scientific baseline, there is no way to know whether the program's performance might be improved by moving the generators to more suitable locations. In a warming climate, it is possible that some mountains have gained seeding suitability and others have lost it. In Lower Basin states, the U.S. Bureau of Reclamation and Utah Division of Water Resources are working together to support scientific research into cloud seeding (Pohkarel et al. 2021a). However, regional and integrated research is needed to assess the degree of future water gains through cloud seeding.

6. Integrated Activities

Three crosscutting topics emerged from the disciplinary, cross-disciplinary, and crosscutting workshop discussions: extreme events, transferable knowledge, and actionable science. These topics emphasize the cross-disciplinary nature of integrated mountain hydroclimate (IMHC) challenges and represent example science questions that the community can address together. Integrated IMHC activities are necessary to solve the research gaps identified in this report because mountain hydroclimates are fundamentally characterized by extremes across spatial and temporal scales. Additionally, integrated IMHC research is needed to address challenges for predicting and understanding the role of IMHC systems and their feedbacks and impacts on humans across scales.

- **Extreme Events** — How are extreme events defined, and what integrated activities may help advance observation and modeling of these events in mountain regions, including their upstream influence and downstream impacts?
- **Transferable Knowledge** — How can knowledge transfer be enabled through integrated activities across mountain regions with different geographies, topographic features, climate and hydrological regimes, human systems, and socioeconomics?
- **Actionable Science** — What integrated activities may help advance use-inspired research and actionable science for mountain regions? Are there stakeholders concerns more unique to mountain regions?

Extreme Events. Extreme events and disturbances are typically defined relative to a historical baseline, but this definition does not necessarily translate into their impacts. There is broad agreement on the need to redefine extreme events in terms of their impacts, as determined by stakeholders based on the unique characteristics of each mountain system. Stakeholder perspectives include topics on miracle springs, large dust storms and wildfires, extreme runoff, and megadroughts and provide input on research to consider the full realm of impacts spanning vegetation to water quality. The sequencing of extreme events and compounding disturbances also matters. Using extreme-producing phenomena as a central focus for investigating processes and impacts presents several opportunities: (1) designing experiments and field sites with extreme events as the central motivating research factor, (2) developing flexible and rapidly deployable mobile platforms and field campaigns, (3) investing in long-term collaborative research stations and networks across different global mountain regions, and (4) developing venues for improving interactions between scientists and stakeholders.

Transferable Knowledge. Because mountains exert dominant influences on atmospheric and terrestrial processes through their impacts on atmospheric circulation, clouds and precipitation, and surface fluxes, mountain hydroclimates share many similarities, but they also differ in their local-to-large-scale environments as well as surface and subsurface properties. Human systems and how they are managed also vary depending on communities and geopolitical context. To enable knowledge transfer, three short-term opportunities exist with current data and modeling tools: (1) leveraging "network-of-network" groups to explore existing datasets across global observatories and identifying process drivers, especially for regions that can be compared based on their similarities and uniqueness; (2) designing model simulations to inform new measurements needed for different communities; and (3) conducting model intercomparison studies across scales and locations to inform drivers and responses to change.

Actionable Science. Providing predictions and projections to support actionable science requires identifying and minimizing biases in two areas: (1) dynamical simulations are subject to uncertainties and errors due to physics parameterizations, model resolutions, and simulation design, and (2) observations are subject to sampling errors, uncertainties in retrieval algorithms, and instrument accuracies. To advance actionable science, stakeholder engagements provide important opportunities for defining the requirements and needs for simulations and observation data, co-production of knowledge and data, and developing regional themes around extreme events that have disproportionate societal impacts. There is a research opportunity to leverage existing stakeholder engagements to improve the understanding of the means, variabilities, and extremes of mountain hydroclimate and to quantify risk tolerance in the decision-making process.

7. Interagency Collaboration Opportunities

Atmosphere. These panel members highlighted a broad range of ongoing activities to develop understanding of key physical quantities connecting atmosphere and surface (SPLASH – NOAA), advance understanding and modeling of water cycle processes and extreme events (WACCEM, E3SM – DOE), parameterize heterogeneous subgrid exchange between land and the atmosphere (CLASP – DOE, NOAA, NASA), and understand the 4D evolution of processes controlling convective lifecycle and impacts near complex terrain (RELAMPAGO/CACTI – NSF, DOE, NASA, NOAA). The DOE E3SM modeling, simulation, and prediction project, which focuses on the water cycle, biogeochemical cycle, and cryosphere processes, was also briefly discussed. Both observations and modeling are key elements of these projects, with efforts toward developing datasets for model evaluation, model intercomparison, integrating data across multiple measurement platforms, modeling across scales (LES to ESM), model-data fusion, development of analysis and diagnostic tools, and enhancement of observing networks identified as opportunities for future collaborations.

Terrestrial. On the Terrestrial panel, many state-federal-local and research network groups presented their ongoing projects and work. A wide range of activities were discussed including the DOE Watershed Function SFA, Slate River Floodplain Hydrobiogeochemistry SFA, the HJ Andrews LTER site, Critical Zone networks, USGS IWP, and NASA SNOWEx programs. Current collaborations were highlighted across all the groups. A main point of focus of this interagency collaboration topic was to highlight what a successful collaboration might require. Many synergistic ideas emerged including ensuring the lines of communication, trust, and sharing were clear and central to the collaborative vision; coordinating activities around common field sites and models with a goal of co-creating joint outputs such as symposia and publications; and developing a shared vision for core integrated critical zone and water (field and modeling) experiments across a variety of scales.

Human. Panelists introduced three DOE-funded projects (PCHES, IM3, and GCIMS) featuring development and use of integrated modeling tools and analysis methods to advance understanding of coupled human-physical systems, their complex interactions, their risk and response behaviors, and their evolution, vulnerability, and resilience. Understanding and quantifying uncertainty is a common challenge in these projects. An EPA-funded project (ICLUS) that produces population and land-use projections to inform national global change assessments was also discussed. Broad collaborations are key for bridging disciplinary methods, tools, and concepts to address complex interactions. Collaborations are facilitated by sharing of data, tools, and models within the teams and with the broader communities. Open-source models, FAIR principles, diverse modes of communications, and building communities of practice were highlighted as key success factors for collaborations.

Human-Terrestrial-Atmosphere Interactions. Interactions among terrestrial, atmospheric, and human systems was the focus of this interagency panel. The panel included representatives from many different federal programs including the USGS PUMP-IWP Program, DOE EPSCoR, DOE BER activities including the SAIL field campaign, Watershed Function SFA, and IM3 SFA. All programs in some form had focused projects on various aspects of mountain systems. These included developing advanced hydroclimate modeling tools, evaluating the interdependence of natural and human systems and the implications to decision-making capabilities, and advancing efforts to fill in broad data gaps. Opportunities for collaborative research across terrestrial-atmospheric-human systems include sharing data compilations, choosing watersheds as "model basins," developing co-investments in data and model intercomparison projects and "Network-of-network" grassroots groups, and recognizing that the lack of subsurface observations is one of the largest data gaps for modeling. Many of the teams recognized the idea that a number of projects are already poised to facilitate successful collaborations and that these collaborations can happen in funded and nonfunded ways. In one example from the USGS IWP program, collaboration occurs as "teams-of-teams" approaches across agencies, while in others this occurs through co-investments and directed funding. To facilitate collaborative research, much work is needed before the science can begin, and this includes activities such as building and expanding linkages to state and local agencies, collectively deciding on next-generation observatories and modeling tools (AI/ML approaches), and navigating the collaborative process with expert project coordinators.

Integrated Mountain Hydroclimate Variability and Change. A diverse set of projects funded by multiple agencies was introduced by members of this panel. These projects aim to improve modeling of subgrid land-atmosphere coupling (CLASP – NASA, NOAA, DOE), understand how warming impacts eco-hydro-climatology of mountain systems (Molotch – NASA), co-define climate change refugia to inform management of mountain headwater systems (Musselman – NSF), improve understanding of fundamental hydrological and ecological processes and interactions (Oishi – USDA), advance understanding of natural and anthropogenic influences on climate extremes (CASCADE – DOE), advance actionable climate science (HyperFACETS and E3SM – DOE), and understand and characterize the water, energy, and carbon cycles in the Anthropocene (GEWEX RHP). The need to integrate observations from multiple platforms and sampling strategies, model across scales, and develop and use new diagnostics and analysis tools has driven broad collaborations within the project teams. Several projects include strong stakeholder engagements for co-production of knowledge. Different forms and topics of collaborations (e.g., observation, model, and forecast intercomparison, leveraging data from field campaigns, cross-site syntheses) were also identified as opportunities.

Societal Connections. The Societal Connections panel highlighted the need for Research-2-Operations (R2O) and Operations-2-Research (O2R) development cycles. Speakers from the DOE HyperFACETS project, U.S. Bureau of Reclamation, NOAA/NIDIS, USGS, and NSF gave updates on the status of their programs/projects and opportunities for collaborations. Topics included the novel use of cloud seeding to enhance precipitation in the western United States, managing drought risks and impacts, and understanding water storage in mountain catchments. All speakers highlighted the need to improve observational datasets, enhance numerical tools, pilot operational products, and assess model deficiencies that limit the skill of water prediction—specifically using an iterative R2O/O2R development lifecycle. Critical to the success of these efforts is access to new funding opportunities with collaboration central to the opportunity, a shared understanding of the prediction problem from end-to-end by both parties, a shared focus on delivering enhanced capabilities to specific stakeholders, the ability to work closely with end users and local partners, the ability to learn the environment of stakeholders and end users, and having a shared systems-engineering focus to research. An approach geared toward stakeholder co-production of research will require iterative discussions and decision-relevant metrics to guide research activities, all established from the beginning before the research begins, and the flexibility to adapt the science when stakeholder needs move in a different direction.

Finally, a panel of interagency program managers reflected on key takeaways for collaborations, noting the many forms of collaborations across smaller and larger projects that have grown organically within and across agencies. They also noted the following needs:

- More experts and boundary spanners to integrate across research.
- Expertise and funding support for stakeholder engagement.
- Innovative technique, designs, and strategies for new data collection, including concurrent and co-located measurements.
- Strategies for data sharing, storage, and management.
- Support for diverse and inclusive approaches for innovative research.
- Open science, interoperable models, and the FAIR principles.
- Business models of successful collaborations, including both bottom-up and top-down approaches.
- Support for research as well as infrastructure needed for the research.
- Sustained funding and the long-term vision to provide continuity.
- Defining priority regions on which to focus resources and enhance collaborations.
- Addressing operational challenges for supporting cross-programs and cross-agency collaborations.

Appendix A. Workshop Participants

Session 1: DOE Focus (November 15-16, 2021)

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Session 2: Interagency Collaborations (January 19, 2022)

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Appendix B. Agenda

Session 1: DOE Focus

Day 1 Agenda — November 15, 2021

11 AM ET/ 8 AM PT – **Introduction, Meeting Expectations, Workshop Charge**

Workshop Co-chairs: *Michelle Newcomer, Lawrence Berkeley National Laboratory (LBNL); Kristen Rasmussen, Colorado State University; Ruby Leung, Pacific Northwest National Laboratory (PNNL)*

11:15 AM ET/ 8:15 AM PT – **Welcome and Context from DOE**

Gary Geernaert, DOE Earth and Environmental Systems Sciences Division Director
Jennifer Arrigo, DOE Environmental System Science Program Manager

11:30 AM ET/ 8:30 AM PT– **Day 1 Plenary: Systems Perspectives and Stage Setting Talks**

- **Terrestrial Systems**
  Ying Fan Reinfelder, Rutgers University
- **Human Systems**
  James Eklund, Eklund Hanlon, LLC
- **Atmospheric Systems**
  Roy Rasmussen, National Center for Atmospheric Research (NCAR)

12:30 PM ET/ 9:30 AM PT– **Break**

12:50 PM ET/ 9:50 AM PT– **Charge to Breakouts**

12:55 PM ET/ 9:55 AM PT– **Break**

12:55 PM ET/ 9:55 AM PT – **Breakout #1: Disciplinary Groups**

Atmospheric Systems
Topic Co-leads: *Adam Varble, PNNL; Alan Rhoades, LBNL*
Panelists: *Ana Barros, University of Illinois, Urbana-Champaign; Nikolina Ban, University of Innsbruck; Benjamin Hatchett, Desert Research Institute (DRI); Justin Minder, University at Albany*

Terrestrial Systems
Topic Co-leads: *Matthias Sprenger, LBNL; Nate Chaney, Duke University*
Panelists*: Hoori Ajami, University of California, Riverside; Teklu Tesfa, PNNL; Daniella Rempe, University of Texas, Austin; Noah Molotch, University of Colorado, Boulder*

Human Systems
Topic Co-leads: *Nathalie Voisin, PNNL; Andy Jones, LBNL*
Panelists: *Jeff Arnold, U.S. Army Corps of Engineers; Lejo Flores, Boise State University; Nathalie Voisin, PNNL; Mark Wigmosta, PNNL*

2:30 PM ET/ 11:30 AM PT – **Break**

2:45 PM ET/ 11:45 AM PT – **Breakout #2: Cross-Disciplinary Groups**

Atmosphere–Terrestrial Systems
Panelists: *Susan Hubbard, LBNL; Alex Hall, University of California, Los Angeles; Gautam Bisht, PNNL; Jessica Lundquist, University of Washington; James McNamara, Boise State University*

Terrestrial–Human Systems
Panelists: *Peter Nico, LBNL; Charles Luce, U.S. Forest Service; Jon Herman, University of California, Davis; Charuleka Varadharajan, LBNL*

Human–Atmosphere Systems
Panelists: *Christine Shields, NCAR; Yun Qian, PNNL; Simon Wang, Utah State University; Kristen Rasmussen, Colorado State University*

4:00 PM ET/ 1:00 PM PT – **Break**

4:15 PM ET/ 1:15 PM PT – **Report-Out from Breakout Sessions #1 and #2; Identify Integrated Research Topics (For Day 2 Breakout #4)**

5:30 PM ET/ 2:30 PM PT **– Adjourn for Day 1**

Day 2 Agenda — November 16, 2021

11:30 AM ET/ 8:30 AM PT – **Day 2 Plenary: Cross-Cutting Themes**

- **Atmosphere-Terrestrial-Human System Interactions**
  Ian Kraucunas, PNNL
- **IMHC Climate Variability and Change**
  Ben Livneh, University of Colorado
- **Societal Connections**
  Andy Jones, LBNL

12:30 PM ET/ 9:30 AM PT – **Breakout #3: Crosscutting Themes**

Atmosphere–Terrestrial-Human System Interactions
Topic Co-leads: *Peter Thornton, Oak Ridge National Laboratory (ORNL); Naresh Devineni, City University of New York; Andres Prein, NCAR*
Panelists*: Nina Oakley, Scripps; Peter Thornton, ORNL; Naresh Devineni, City University of New York; Andres Prein, NCAR*

IMHC Climate Variability and Change
Topic Co-leads*: Erica Woodburn, LBNL; Paul Ullrich, University of California, Davis; Ning Sun, PNNL*
Panelists: *Adrienne Marshall, Colorado School of Mines; Dan Feldman, LBNL; Ruby Leung, PNNL; Xiaodong Chen, PNNL*

Societal Connections
Topic Co-leads: *McKenzie Skiles, University of Utah; Simon Wang, Utah State University, Ian Kraucunas, PNNL*
Panelists*: Jim Prairie, U.S. Bureau of Reclamation; Daniella Hirschfeld, Utah State University; Jake Serago, Utah Division of Water Resources; Michelle Newcomer, LBNL; Ning Sun, LBNL*

2:00 PM ET/ 11:00 AM PT – **Break**

2:30 PM ET/ 11:30 AM PT – **Breakout #4: Integrated Research Activities**

Group A
Breakout Leads: *Peter Thornton, Erica Woodburn, Simon Wang*

Group B
Breakout Leads: *Naresh Devineni, Paul Ullrich, McKenzie Skiles*

Group C
Breakout Leads: A*ndreas Prein, Ning Sun, Ian Kraucunas*

4:00 PM ET/ 1:00 PM PT – **Break**

4:15 PM ET/ 1:15 PM PT – **Report-Out from Breakout Sessions #3 and #4**

5:00 PM ET/ 2:00 PM PT – **Open Discussion and Closing Remarks**

5:30 PM ET/ 2:30 PM PT – **Adjourn**

Session 2: Interagency Collaborations

January 19, 2022

11 AM ET/ 8 AM PT – **Opening Session**

- 11:00 AM ET/ 8:00 AM PT – **Welcome from Workshop Co-chairs**
  Ruby Leung, Pacific Northwest National Laboratory (PNNL); Michelle Newcomer, Lawrence Berkeley National Laboratory (LBNL); Kristen Rasmussen, Colorado State University
- 11:05 AM ET/ 8:05 AM PT – **Welcome and Perspectives on IMHC from DOE**
  Gary Geernaert, DOE Earth and Environmental Systems Sciences Division Director
- 11:12 AM ET/ 8:12 AM PT – **IMHC in the DOE EESSD Portfolio**
  Jennifer Arrigo, DOE Environmental System Science Program Manager
- 11:15 AM ET/ 8:15 AM PT– **IMHC Workshop Session 1 Summary**
  Ruby Leung, Michelle Newcomer, Kristen Rasmussen

11:55 AM ET/ 8:55 AM PT – **Break and Transition to Panel**

12:00 PM ET/ 9:00 AM PT– **IMHC Disciplinary Sessions**

Federal and federally funded scientists share information on IMHC-relevant projects and research across various federal agencies in three disciplinary areas. Each panelist shared project/research information and commented on what they might see as interagency opportunities (e.g., challenges that other agencies/projects could help with as well as leveraging or synergy opportunities)

12:00 PM ET/ 9:00 AM PT – **Atmosphere Panel**

- **SPLASH**, funded by the National Oceanic and Atmospheric Administration (NOAA)
  Gijs de Boer, NOAA
- **E3SM, HyperFACETS, ICOM, WACCEM**, funded by DOE
  Ruby Leung, PNNL
- **Climate Process Teams**, funded by National Science Foundation (NSF), NOAA, and DOE
  Po-Lun Ma, PNNL
- **RELEMPAGO/CACTI**, funded by NSF and DOE
  Steve Nesbitt, University of Illinois, Urbana-Champaign
- **Wildfire Smoke, Missoula Fire Lab**, funded by U.S. Department of Agriculture (USDA) and U.S. Forest Service (USFS)
  Shaun Urbanski, USFS

12:40 PM ET/ 9:40 PM PT – **Terrestrial Panel**

- **Floodplain Hydro-biogeochemistry Science Focus Area (SFA),** funded by DOE
  John Bargar, SLAC National Accelerator Laboratory
- **CZ-Net Dynamic Water**, funded by NSF
  Holly Barnard, University of Colorado, Boulder
- **Integrated Water Science Basins**, funded by USGS
  Katie Skalak, USGS

- **HJ Andrews Experimental Forest**, funded by USDA and USFS
  Brooke Penaluna, USFS
- **Modeling Mountain Land Surface Processes**, funded by DOE
  Peter Thornton, Oak Ridge National Laboratory
- **SnowEx**, funded by NASA
  Carrie Vuyovich, NASA

1:20 PM ET/ 10:20 AM PT – **Human Systems Panel**

- **PCHES**, funded by DOE
  Danielle Grogan, University of New Hampshire
- **Terrestrial Ecology Program**, funded by NASA
  Kathy Hibbard, NASA
- **HyperFACETS**, funded by DOE
  Andy Jones, University of California, Berkeley
- **ICLUS**, funded by the U.S. Environmental Protection Agency (EPA)
  Philip Morefield, EPA
- **IM3**, funded by DOE
  Patrick Reed, Cornell University
- **GCIMS**, funded by DOE
  Tom Wild, PNNL

2:00 PM ET/ 11:00 AM PT – **Break**

2:15 PM ET/ 11:15 AM PT – **Atmosphere-Terrestrial-Human System Interactions**

Federal and federally funded scientists share information on IMHC-relevant projects and research across various federal agencies in three crosscutting topics that were discussed during the November 2021 workshop. Each panelist shared project/research information and commented on what they might see as interagency opportunities (e.g., challenges that other agencies/projects could help with as well as leveraging or synergy opportunities)

2:15 PM ET/ 11:15 AM PT – **Atmosphere-Terrestrial-Human System Interactions**

- **Integrated Water Prediction (IWS) – PUMP**, funded by USGS
  Hedeff Essaid, USGS
- **SAIL**, funded by DOE
  Dan Feldman, University of California, Berkeley
- **Investigating Subsurface Flow in Mountainous Catchments**, funded by DOE EPSCoR
  Payton Gardner, University of Montana
- **Watershed Function SFA, East River Community Watershed**, funded by DOE
  Ken Williams, LBNL
- **Modeling A-T-H Interactions,** funded by DOE
  Nathalie Voisin, PNNL

2:55 PM ET / 11:55 AM PT – **Climate Variability and Change in Mountain Systems**

- **Interagency Climate Process Teams**, funded by DOE, NOAA, and NSF
  Nate Chaney, Duke University; Po-Lun Ma, PNNL
- **Niwot Ridge LTER**, funded by NSF
  Noah Molotch, University of Colorado, Boulder
- **Co-defining Climate Refugia to Inform the Management of Mountain Headwater Systems**, funded by NSF
  Keith Musselman, University of Colorado, Boulder
- **Coweeta Hydrologic Laboratory**, funded by USDA and USFS
  Chris Oishi, USFS
- **CASCADE, funded by DOE**
  Alan Rhoades, LBNL
- **U.S. Regional Hydroclimate Project Affinity Group**, funded by GEWEX
  Tim Schneider, NOAA

3:35 PM ET/ 12:35 PM PT – **Societal Implications of IMHC**

- **Upper Gunnison (CO) Research on Weather Modification**, funded by U.S. Bureau of Reclamation (BoR)
  Lindsey Bearup, BoR
- **ASO and Forecasting,** funded by NSF
  David Gochis, University Corporation for Atmospheric Research
- **HyperFACETS,** funded by DOE
  Andy Jones, University of California, Berkeley
- **Drought/ NIDIS**, funded by NOAA
  Joel Lisonbee, University of Colorado, Boulder
- **New Science, Tools, and Observations to Couple Geodesy with Hydrology for Modeling, Water Storage Change, and Streamflow Forecasting in Mountain Watersheds**, funded by NSF
  Hilary Martens, University of Montana

4:15 ET/ 1:15 PM PT **– Break**

4:30 PM ET/ 1:30 PM PT **- Closing Session**

4:30 PM ET **– Program Manager Panel**

Each agency panelist is asked to provide 3 to 5 minutes of opening remarks to share agency/programmatic interests in IMHC and to discuss opportunities or synergies they identified for their agency/program from the IMHC science presented during the earlier part of the day.

Moderator: *Jennifer Arrigo, DOE*
Panelists: *Nick Anderson, NSF; Jared Entin, NASA; Jin Huang, NOAA; Laura Lautz, NSF; David Lesmes, USGS*

5:15 PM ET/ 2:15 PM PT – **Final Remarks/ Discussion**

5:30 PM ET/ 2:30 PM PT **- Close of Workshop**

Appendix C. References

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